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ANALYSIS OF REMOTE OPERATING SYSTEMS FOR SPACE-BASED SERVICING OPERATIONS, FINAL REPORT

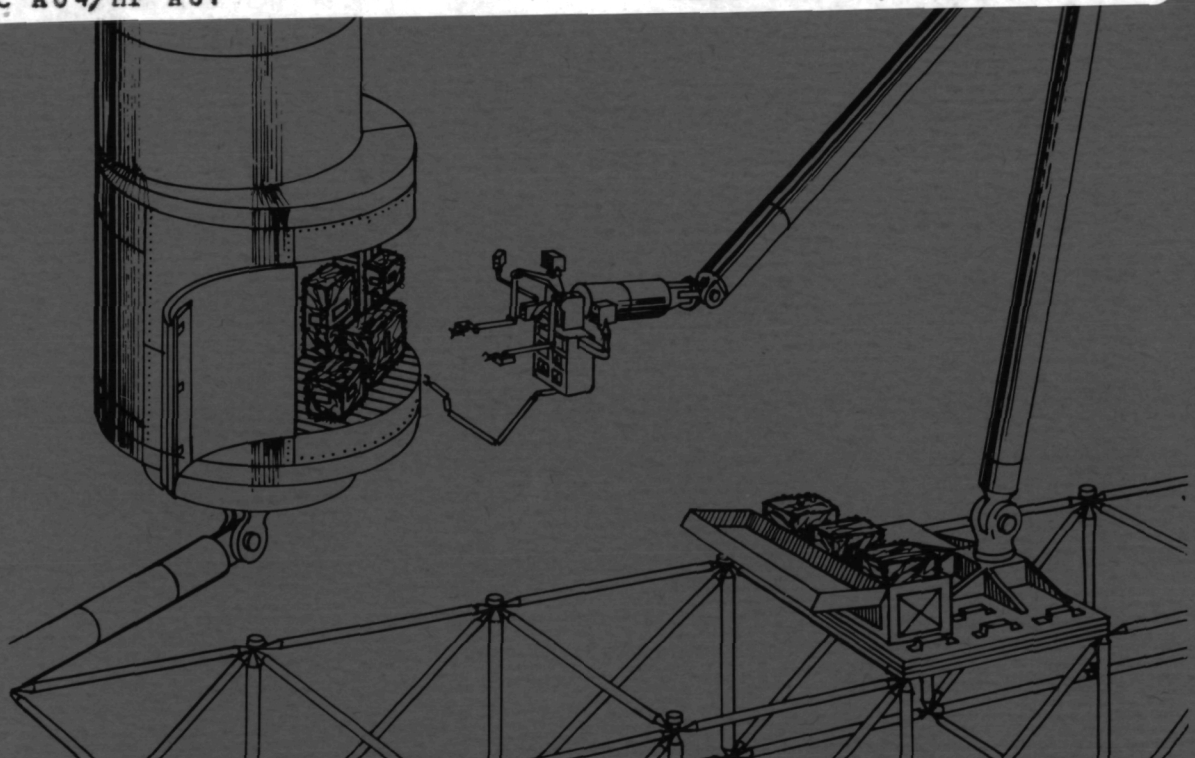
Vol. 2 — Study Results

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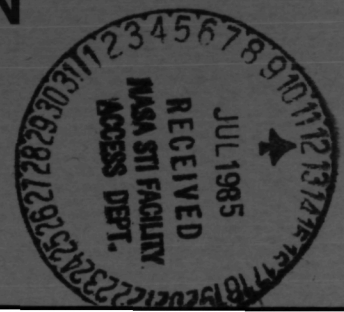
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GRUMMAN CORPORATION



ANALYSIS OF REMOTE OPERATING SYSTEMS FOR SPACE-BASED SERVICING OPERATIONS, FINAL REPORT

Vol. 2 — Study Results

prepared for
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, TX 77058

by
Grumman Corporation
Bethpage, NY 11714

NAS9-17066
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PREFACE

This study was conducted for the Lyndon B. Johnson Space Center under NASA Contract NAS9-17066 by the Grumman Aerospace Corporation. Mr. Lyle M. Jenkins was NASA's Technical Monitor and Mr. Darrell R. Matula was the Contract Specialist for the study. Mr. Roy E. Olsen was the Grumman Study Manager.

The nine-month study was started on 27 February 1984. Phase 1 was completed on 27 May 1984 and Phase 2 was completed on 27 November 1984. A wide range of potential applications for space-based servicing, using remotely operated systems, have been identified and system concepts have been defined. A technology development program compatible with Space Station planning is also defined.

The major Grumman contributors to this study were:

- Erik Eriksen Deputy Study Manager & Program Planning Task Leader
- Raymond Pratt Mission Requirements Task Leader
- Stanis Coryell Design Concepts Task Leader
- Chauncey Knapp Design Concepts
- Christopher Horan Design Concepts
- Vahe Jordan System Costs

The Final Report for the study is presented in two volumes:

- Volume 1 Executive Summary
- Volume 2 Study Results

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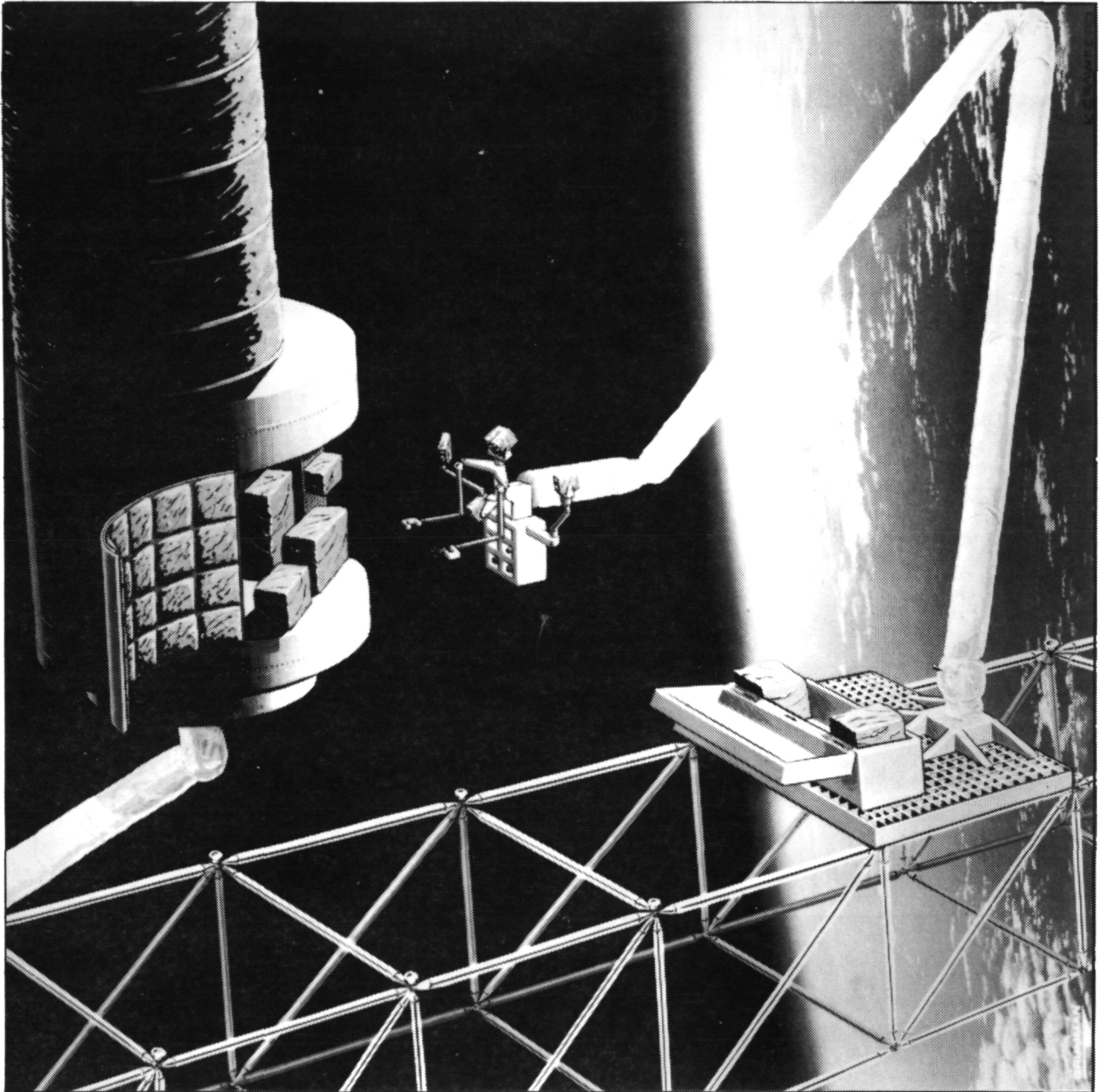
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1 - INTRODUCTION

This volume presents the results of the study entitled "Analysis of Remote Operating Systems for Space-Based Servicing Operations." An overview of the study is presented in Volume 1, Executive Summary. The development of remotely operated systems for space station and free flyer servicing is addressed. Included are the identification of system requirements and the allocation of tasks to different types of remote systems. The goal of these systems is not to replace the human but to augment and extend the human's capabilities in order to increase productivity and safety without sacrificing the human's unique decision-making skills.

2 - STUDY OBJECTIVES

2.1 OBJECTIVES

The purpose of this study was to analyze and develop the requirements for remote operating systems as applied to space-based operations for the servicing, maintenance and repair of satellites. The study defines remote operating system options, develops preliminary space station interface and support requirements, and scopes options for technology development and demonstration. Remote operating systems are defined as the equipment which provides the ability to perform useful work in space at distances ranging from close proximity to thousands of miles from a human operator.

2.2 GROUND RULES

The major ground rules established for the study were as follows:

- Servicing operations on and in conjunction with the space station will be considered; servicing functions on the space station include the maintenance of subsystems of a satellite which has been retrieved for service; servicing in conjunction with the space station includes *in situ* operations such as module replacement on a space platform vehicle controlled from the space station
- Activities involving hazards, repetition, or intermittent tasks will be included
- Remote operating systems of three basic types (teleoperation, telepresence and robotic) will be considered
- Systems development will emphasize early flight systems.

3 - STUDY APPROACH

3.1 STUDY LOGIC

The study was conducted in two distinct phases as shown in Fig. 3-1. Phase 1, Requirements Analysis, consisted of the development of servicing requirements to establish design criteria for remote operating systems. Key inputs to this analysis were the mission models from related studies.

Phase 2, Concepts Development, defined preferred system concepts and development plans which met the requirements established in Phase 1. In Task 2, remote operating system concepts were developed and analyzed to identify desirable operational and conceptual approaches for the selected mission scenarios. The potential impact of such systems incorporated into the design of the space station were identified in Task 3. Remote operating systems design issues, such as mobility, which are effected by the space station configuration, were addressed. Baseline space station configurations were a key input to this task. Programmatic approaches for technology development, testing, simulation, and flight demonstration in support of remote operating systems development were defined in Task 4. This task included program plans, schedules, and estimated costs for 1) a supporting development program to establish technology readiness, and 2) a production program to support early space station operations.

3.2 SCHEDULE

The schedule for the study, shown in Fig. 3-2, includes milestones for briefings, documentation and task/subtask performance periods.

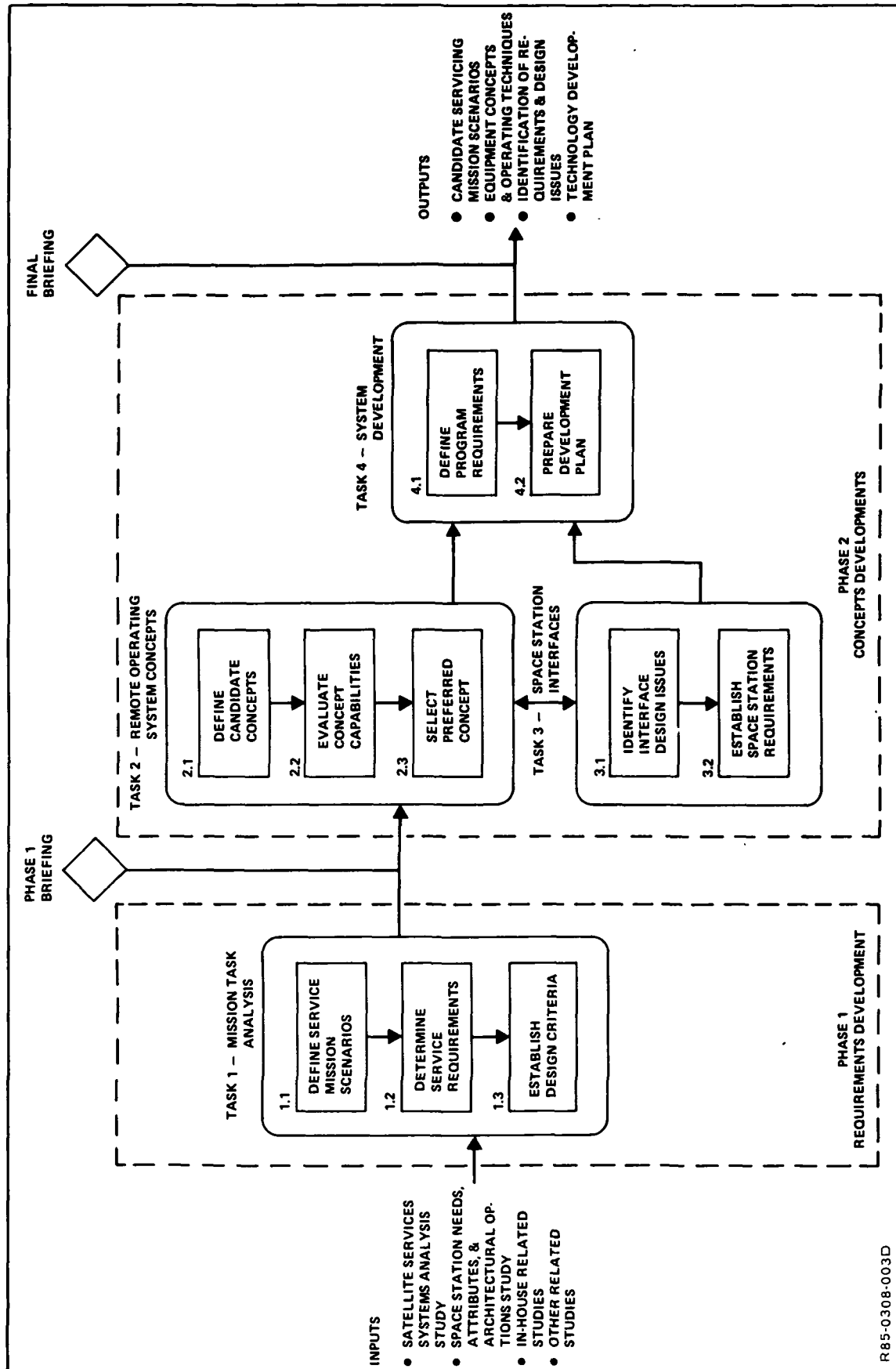
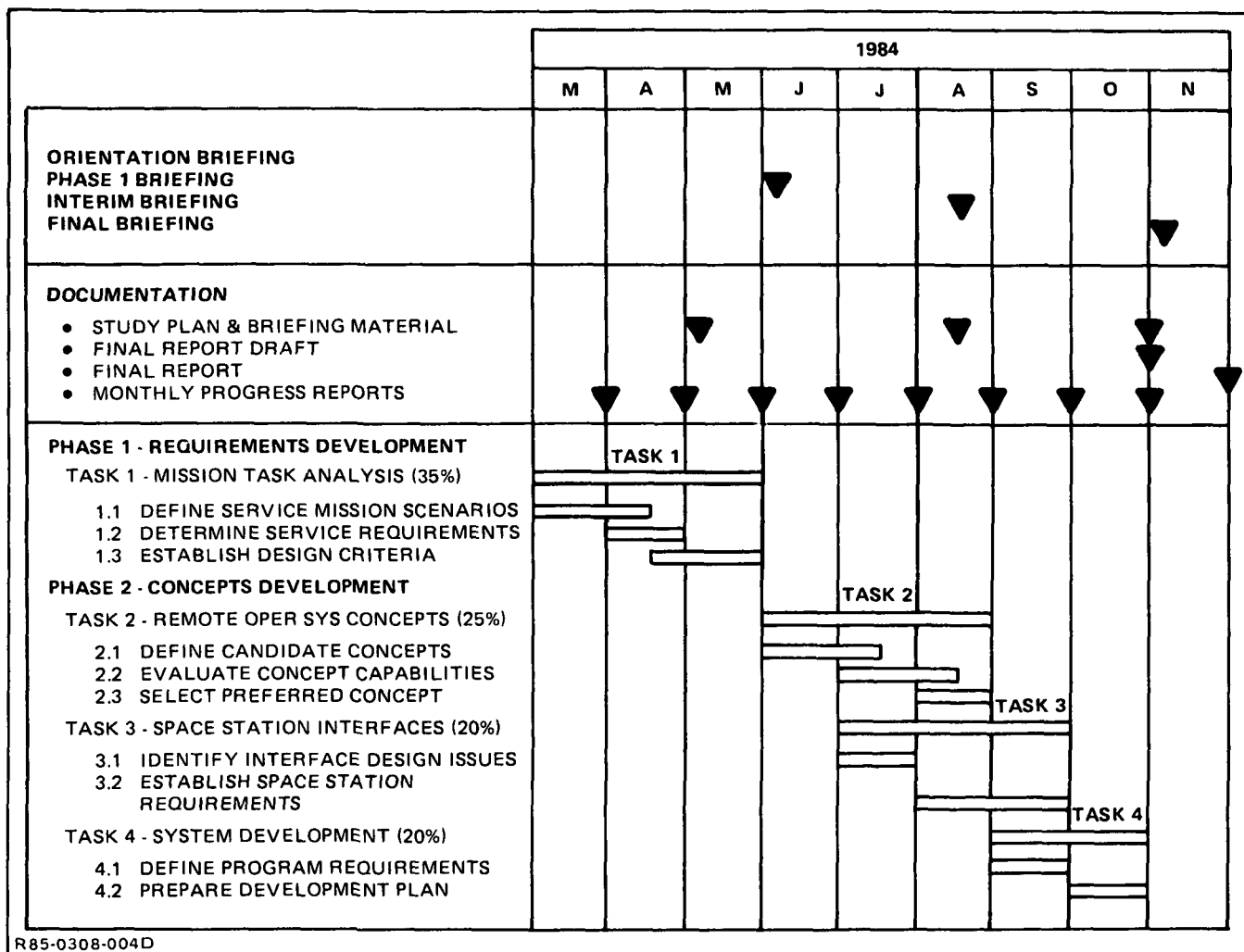


Fig. 3-1 Study Logic & Major Outputs



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Fig. 3-2. Study Schedule

4 - REQUIREMENTS DEVELOPMENT

The development of requirements has considered the full range of in-orbit servicing tasks which may be required. Figure 4-1 presents the range of general functions extending from relatively simple resupply to the upgrading of a satellite by incorporating new equipment. These functions may be required as a result of anticipated events, such as mechanical wear, or from unforeseen, uncontrollable factors such as a design flaw.

4.1 MISSION SCENARIOS

Three service sites were considered in this study:

- On board service at a space station, performing external service on the station and on spacecraft temporarily attached to the station
- Remote operations in low earth orbit (LEO) on satellites or space platforms
- Remote operations in geosynchronous orbit (GEO) on satellites or space platforms.

The NASA Space Systems Technology Model, January 1984 issue, and the NASA/LaRC Space Station Mission Model Data Base, and related studies (Ref. 1, 2, and 3) were used as sources of candidate mission scenarios. Commercial, science, applications and technology development missions planned or proposed during the 1990s were considered.

SERVICING FUNCTION	REASONS FOR SERVICING	BASIC SERVICE REQUIREMENT
RESUPPLY	UNPLANNED LOSS OF EXPENDABLE <ul style="list-style-type: none">● FAILURE● OTHER	REFILL TANKS OR ADD TANKS
	PLANNED USE OF EXPENDABLE <ul style="list-style-type: none">● LOWER INITIAL LAUNCH WEIGHT	
REPLACE/REPAIR	UNPLANNED FAILURE <ul style="list-style-type: none">● DESIGN FLAW● RANDOM FAILURE● WEAROUT● DELIVERY SYSTEM FAILURE/ANOMALY	<ul style="list-style-type: none">● REMOVE AND/OR REPLACE FAILED EQUIPMENT● CORRECT CAUSE OF FAILURE
RECONFIGURE	PLANNED OR UNPLANNED NEW OR ADDED MISSIONS	ADD NEW EQUIPMENT AND/OR MODIFY ARRANGEMENT OF OLD EQUIPMENT
UPGRADE	PLANNED OR UNPLANNED NEW TECHNOLOGY	ADD AND/OR MODIFY EQUIPMENT

SELECTED

- FLUID TRANSFER
- TANK REPLACEMENT
- ELECTRONICS REPLACEMENT
- "REPAIR"
- CONSTRUCTION

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Fig. 4-1 Requirements Development Service Tasks

An initial selection of fourteen candidate missions (Fig. 4-2) was made covering the three service sites described above. Servicing on-board the space station includes a mission for external subsystems of the station, in addition to attached spacecraft and payloads. Low earth orbit missions include those requiring equipment servicing and assembly operations. Specific missions were selected based on the generic nature of the service to be performed, the mission time frame, the frequency of servicing, and the relationship to other similar service missions.

MISSIONS GENERIC SITES	S.S.	HRS	SIRTF	OMV	OTV	GRO	AXAF	ST	UARS	SASP	TAT	COSMIC	LDR	GEO. PLAT.
ON-BOARD SPACE STATION														
EXTERNAL SUBSYSTEM SERVICING	<input type="checkbox"/>													
ATTACHED PAYLOAD SERVICING		<input type="checkbox"/>	<input type="checkbox"/>											
ATTACHED UPPER STAGE SERVICING				<input type="checkbox"/>	<input type="checkbox"/>									
ATTACHED SATELLITE SERVICING						<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>						
ATTACHED ASSEMBLY & LARGE CONSTRUCTION											<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
LEO REMOTE SERVICING									<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	
GEO REMOTE SERVICING														<input type="checkbox"/>

☒ ARAMIS STUDY MISSIONS

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Fig. 4-2 Candidate Missions

4.2 SERVICE REQUIREMENTS

The service operations for each of the candidate missions were functionally analyzed to identify service tasks. Service operations considered included repair equipment, maintain equipment, replenish consumables, and replace equipment and assemble major elements. Three levels of functions were identified for each mission: first, the type of service to be provided, e.g., replace instruments; second, the specific item requiring service, e.g., subsystem component; and third, the specific functions to implement the service.

The results of the functional analysis were assembled into five groups: fluid transfer, task replacement, equipment/module replacement, maintenance/repair tasks, and assembly/construction. The missions and associated functions for each group are presented in Fig. 4-3 through 4-6. Representative cases were selected in each group as indicated for subsequent detailed analysis.

In the case of fluid transfer (Fig. 4-3), the Orbital Maneuvering Vehicle (OMV) mission was selected because of requirements for refueling up to seventeen times per

MISSION		S.S.	HRS	SIRTF	GRO	OMV	OTV	AXAF	ST	UARS	SASP	TAT	COSMIC	LDR	GEO COMM PLAT
FUNCTION															
<u>FLUID TRANSFER</u>															
PROPELLANT	- N ₂ H ₄	•			•	•	•								
	- H ₂				•	•	•								
	- N ₂ GAS				•	•	•					•		•	
	- H ₂ & O ₂	•				•	•								
COOLANT	- He/Xe/CH ₄										•				
	- CRYO H ₂		•							•	•				
	CRYO Ar/CO ₂										•				
<u>TANK REPLACEMENT</u>															
PROPELLANT	-	•											•		
COOLANT	- SH _e			•											
	SH ₂			•											
	XENON/METHANE														
	AMMONIA/CRYO METHANE														
	ARGON/CO ₂ /XENON														

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Fig. 4-3. Service Functions Identification – Fluid & Gas Replenishment

year. *In situ* Science and Applications Space Platform (SASP) servicing operations are typical of spacecraft that have instruments requiring replenishment of gases. Tank replacement for cryogenic systems is represented by the Advanced X-ray Astrophysics Facility (AXAF) mission which uses several instruments requiring cooling gases.

Spacecraft servicing operations generally require the replacement of electrical equipment or modules (Fig. 4-4). The Gamma Ray Observatory (GRO) mission was selected to represent the replacement of externally-mounted modules of the Multi-mission Modular Spacecraft (MMS) type, which are a proven concept. The SASP mission was chosen to cover the majority of equipment replacement functions which require gaining access to internally mounted equipment.

Maintenance and repair tasks (Fig. 4-5) on the space station are expected to occur frequently because of the high activity level, periodic visits by the Orbiter and continuous manned presence. Contingency retrieval and deployment operations for the GRO mission at the space station was selected to represent these functions.

FUNCTION	MISSION													
	SS	HRS	SIRTF	GRO	OMV	OMT	AXAF	ST	UARS	SASP	TAT	COSMIC	LDR	GEO COMM. PLAT.
<u>EQUIP./MODULE REPLACEMENT</u>				SELECTED							SELECTED			
MMS MODULES				•	•		•		•	•	•		•	
APPENDAGE DRIVE (ANT, S/A, DOOR & RADAR DRIVE)	•			•	•	•	•	•		•	•		•	
REACTION WHEEL				•	•		•	•		•	•		•	
MAGNETIC TORQUER				•	•		•	•		•	•		•	
INSTRUMENT ELECTRONICS MODULE			•	•	•		•	•		•	•	•	•	
INSTRUMENTS	•			•	•		•	•		•	•		•	
RATE GYRO ASSY	•			•	•		•	•		•	•		•	
SENSORS	•		•	•	•	•	•	•		•	•		•	
BATTERIES	•			•	•	•	•	•		•	•		•	
BATTERY CONTROL & REG	•			•	•	•	•	•		•	•		•	
ELECTRONIC EQUIP.	•		•	•	•	•	•	•		•	•		•	
SOLAR ARRAYS	•			•	•		•	•		•	•		•	
FUEL CELLS				•	•	•	•	•		•	•		•	
ANTENNA	•			•	•	•	•	•		•	•	•	•	
THRUSTER	•				•		•	•		•	•		•	
MANUFACTURED PRODUCTS										•				

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Fig. 4-4 Service Functions Identification – Equipment/Module Replacement

FUNCTION \ MISSION														
	SS	HRS	SIRTF	GRO	OMV	OTV	AXAF	ST	UARS	SASP	TAT	COSMIC	LDR	GEO COMM PLAT.
MAINTENANCE/REPAIR TASKS				SELECTED										
• STOW/DEPLOY APPENDAGES				•	•			•						•
• CONNECT/DISCONNECT UMBILICAL				•	•			•						
• JETTISON APPENDAGES				•	•			•						
• THERMAL BLANKETS				•	•			•						
• RADIATOR	•				•					•				
• SOLAR ARRAY	•				•					•				
• CAMERA – REPLACE	•				•	•					•			
• EXTERIOR LIGHT – REPLACE	•				•	•						•		
• EXTERNAL INSPECTION	•				•	•								
• CLEAN WINDOWS/OPTICS	•				•	•								
• HATCH SEAL REPLACEMENT	•				•	•								
• REPAIR EXTERNAL SURFACE	•				•	•								

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Fig. 4-5 Service Functions Identification – Maintenance/Repair Tasks

MISSION		SS	HRS	SIRTF	GRO	OMV	OTV	AXAF	ST	UARS	SASP	TAT	COSMIC	LDR	GEO COMM PLAT.
FUNCTION															
<u>ASSEMBLY & CONSTRUCTION</u>															
<ul style="list-style-type: none">● ALIGN & MATE UPPER STAGE TO S/C● ATTACH SERVICER TO PLATFORM● ASSEMBLE PRESS./STRUCT. MODULE● ASSEMBLE CONSTRUCTION J/G● ASSEMBLE STRUCTURE● ATTACH PANELS● ASSEMBLE SOLAR ARRAYS● DEPLOY BLANKET		<div>●</div>													<div>●●</div>
													<div>●●●●●</div>	<div>●●●●●</div>	<div>●●●●●●●●</div>

SELECTED

SELECTED

SELECTED

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Fig. 4-6 Service Functions Identification – Assembly & Construction

Initial assembly of the space station and replacement of logistics modules was chosen (Fig. 4-6) to include maneuvering, alignment and attachment of large modules. The mating of large payloads to an upper stage was chosen using the GEO Communications Platform in the stowed configuration as the payload to be mated.

The Large Deployable Reflector (LDR) mission was selected as the source of representative mission requirements for in-orbit construction of a complex, large structure.

The selected servicing missions were refined further, as indicated in Fig. 4-7, to provide a baseline set of service tasks to be used for establishing remote system design criteria. Functionally redundant operations or less complex operations required by more than one mission or as part of one mission were eliminated.

The resulting group of seven missions are indicated by the shaded pictures in Fig. 4-8 with the applicable service functions included.

4.3 DESIGN CRITERIA

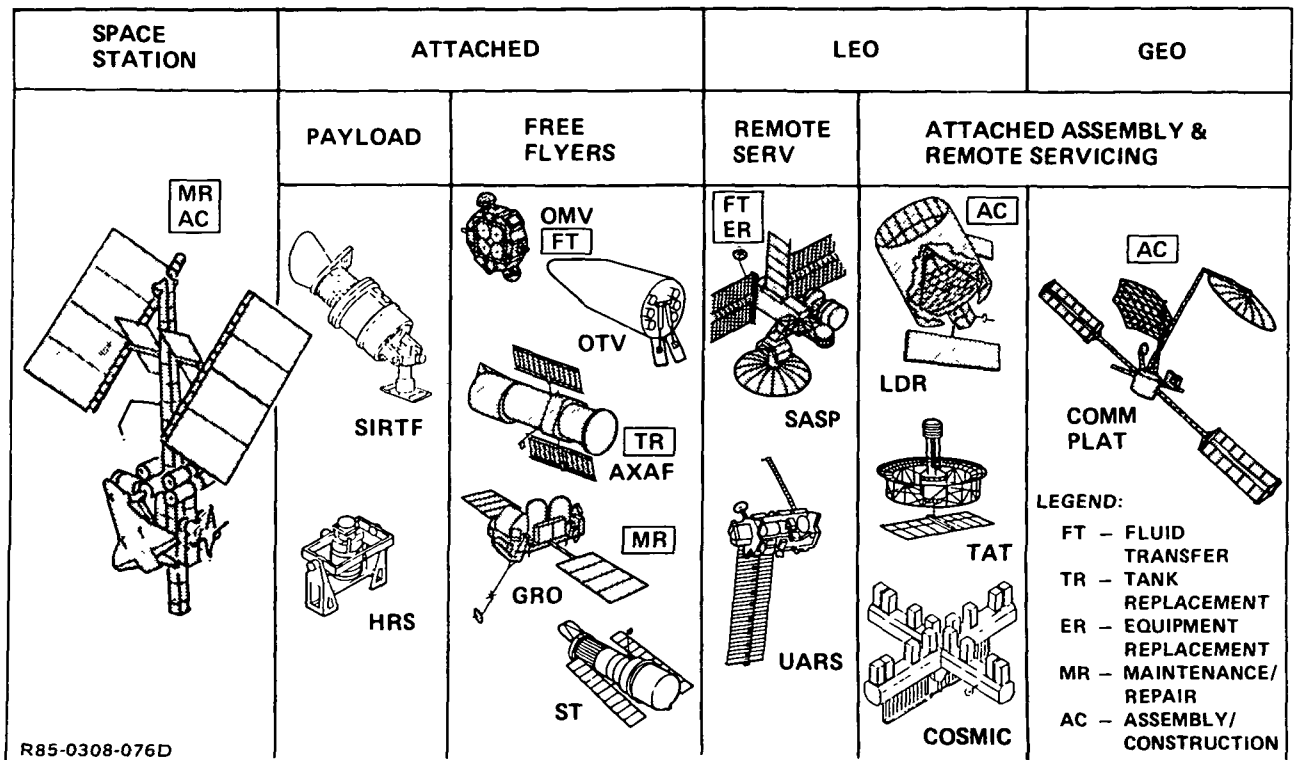
Design criteria for the development of remote operating systems have been established by evaluating the design factors for these systems relative to the mission factors for the representative tasks selected above. These factors are expanded in Fig. 4-9. The significant design issues and the corresponding mission factors which impact them are presented in Fig. 4-10. Physical constraints and special task functions have the broadest effect on design issues, but all mission factors are important.

MISSION	FUNCTION	SPECIFIC OPERATIONS
SPACE STATION	MAINTENANCE & REPAIR	<ul style="list-style-type: none"> • THERMAL BLANKETS • RADIATOR • SOLAR ARRAY • CAMERA REPLACE • EXT. INSPECTION • CLEAN WINDOWS/OPTICS • HATCH SEAL REPLACE
	ASSEMBLY & CONSTRUCTION	• ASSEMBLE PRESS./STRUC. MODULE
OMV	FLUID TRANSFER	<ul style="list-style-type: none"> • N₂H₄ PROPELLANT TRANSFER • GN₂ PROPELLANT TRANSFER
AXAF	TANK REPLACEMENT	<ul style="list-style-type: none"> • XENON/METHANE • AMMONIA/CRYO METHANE • ARGON/CO₂/XENON
GRO	MAINTENANCE & REPAIR	<ul style="list-style-type: none"> • STOW/DEPLOY APPENDAGES • CONNECT/DISCONNECT UMBILICAL • JETTISON APPENDAGES • MMS MODULES
LDR	ASSEMBLY & CONSTRUCTION	<ul style="list-style-type: none"> • ASSEMBLE CONSTRUCTION JIG • ASSEMBLE STRUCTURE • ATTACH PANELS • ASSEMBLE SOLAR ARRAYS • DEPLOY BLANKET
COMM PLATFORM	ASSEMBLY & CONSTRUCTION	<ul style="list-style-type: none"> • ALIGN & MATE UPPER STAGE TO S/C • ATTACH SERVICER TO PLATFORM
SASP	EQUIPMENT/MODULE REPLACEMENT	<ul style="list-style-type: none"> • MMS MODULES • APPENDAGE DRIVES • REACTION WHEEL • MAGNETIC TORQUER • INSTRUMENT ELEC. MODULE • INSTRUMENTS • BATTERIES • ANTENNA • MANUFACTURED PRODUCTS
	FLUID TRANSFER	• HE/XE/CH ₄

SELECTED: ☐

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Fig. 4-7 Service Tasks



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Fig. 4-8 Selected Servicing Missions

SYSTEM DESIGN FACTORS	GENERAL MISSION FACTORS
<ul style="list-style-type: none"> • MANIPULATOR(S) <ul style="list-style-type: none"> – QUANTITY – SIZE – DEXTERITY (DOF, GEOMETRY) – PRECISION • STABILIZER(S) <ul style="list-style-type: none"> – QUANTITY – SIZE – DEXTERITY • END EFFECTORS <ul style="list-style-type: none"> – QUANTITY – COMPLEXITY • VISION SYSTEM <ul style="list-style-type: none"> – SENSOR – LIGHTING • EQUIPMENT STOWAGE <ul style="list-style-type: none"> – SIZE – COMPLEXITY 	<ul style="list-style-type: none"> • PAYLOAD CHARACTERISTICS <ul style="list-style-type: none"> – PHYSICAL SIZE – MASS/INERTIA • OPERATIONAL VOLUME <ul style="list-style-type: none"> – DIMENSIONS – REACH REQUIRED • PHYSICAL CONSTRAINTS <ul style="list-style-type: none"> – OBSTACLES – COMPLEXITY • TASK ENVIRONMENT <ul style="list-style-type: none"> – UNUSUAL CHARACTERISTICS (E.G. TIME DELAY) – REPETITIOUS TASKS • SPECIAL TASK FUNCTIONS <ul style="list-style-type: none"> – MISSION-UNIQUE OPERATIONS – REPAIR FUNCTIONS
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Fig. 4-9. Design Criteria Development Factors

DESIGN ISSUE	MISSION REQMTS AREA	PAYLOAD SIZE	OPERATIONAL VOLUME	PHYSICAL CONSTRAINTS	TASK ENVIRONMENT	SPECIAL TASK FUNCTIONS
SLAVE ARM	•	•	•	•		
CONTROLLERS			•	•		•
CONTROL TECHNIQUES				•	•	•
NO. OF ARMS	•	•	•			•
VISIBILITY	•	•	•	•	•	•
DISPLAYS				•	•	•
END EFFECTORS	•			•		•
SPECIAL TOOLS				•		•
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Fig. 4-10 Remote System Drivers

Each representative mission was examined in detail to arrive at general design criteria. Tank replacement for the AXAF mission is illustrated in Fig. 4-11a as an example of a specific servicing task.

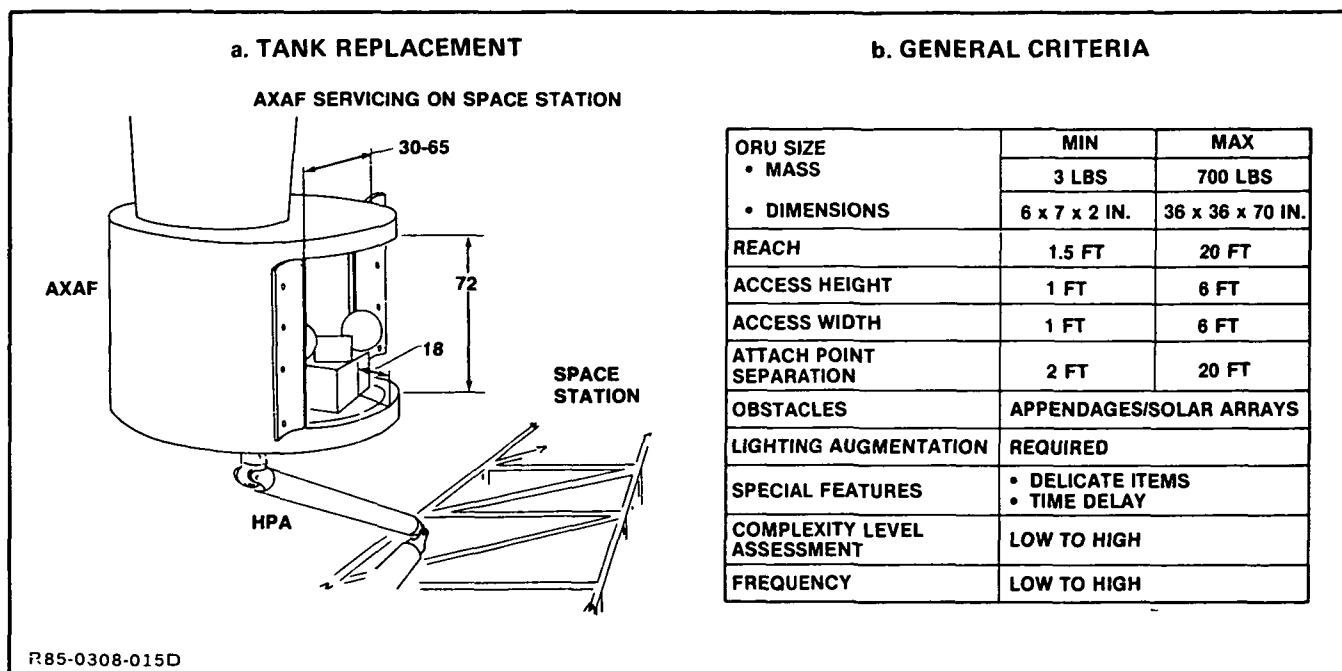


Fig. 4-11 Requirements Development – Design Criteria

Many of the AXAF instruments require gaseous cooling. The replenishment approach we selected is to replace the gas tanks. First, doors must be opened for access to the instruments, then a manipulator can reach into the instrument carousel to grasp the tank. Isolation valves must have previously been closed and the tank electrically isolated. Plumbing lines must be disconnected and the tank must be structurally released.

A manipulator requires support close to the work area and must reach 2-1/2 ft into the carousel through an opening 30 in. wide x 72 in. high.

The resulting general design criteria based on such analysis is presented in Fig. 4-11b. The minimum and maximum values for the parameters shown were selected based on analysis of the specific servicing tasks. The maximum values indicated for reach and attach point separation were chosen as realistic design values although exceptions might be encountered for certain missions. These cases would be treated as mission-unique requirements with additional, special equipment needed.

The carrier vehicle or device, such as a railed crane, which positions the remote system and the device which holds and positions a spacecraft being serviced, have a significant effect on design requirements of the remote system. The selected values are considered to be reasonable design criteria.

The wide variations in complexity level and servicing frequency have been considered in the concepts development effort for comparing the candidate concepts. For example, an infrequently performed, complex service operation will generally have a major impact on the design of a robotic servicing system. These evaluations have been made during the Task 2 portion of the study.

5 - CONCEPTS DEVELOPMENT

This section develops concepts for remote operating systems which meet the requirements of the reference missions established in the preceding section. Remote operating systems, whether for servicing of the space station or of free flyers, are, in general, comprised of a complement of equipment, both remotely located and at the location of the operator. This complement of equipment includes the remote equipment which actually performs the desired task, the associated equipment which moves to and from the worksite, and the control stations which provide for direction of the remote operations.

The interrelationships between the various elements which comprise such a system are shown schematically by Fig. 5-1. The *work system* is defined as the element which performs the direct contact operations associated with the task, such as removing an electrical module. The work system may be held by a *positioning arm* and the work object; e.g., the satellite being repaired, may be held by *handling equipment*. *Storage racks* may be required to temporarily hold equipment, such as replacement units or special tools. This equipment may be mounted on a *transport vehicle*. The handling equipment may be attached to the transport vehicle

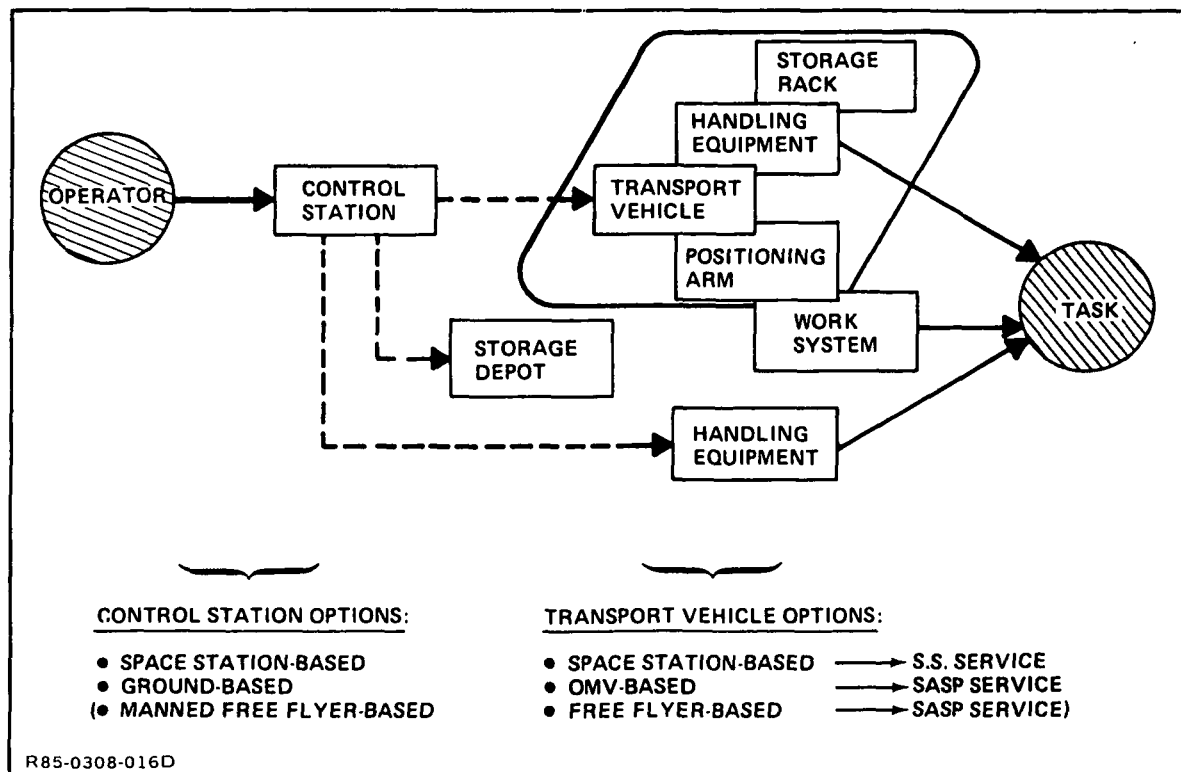


Fig. 5-1 Remote Operating System Elements

or separately mounted at the worksite. A *storage depot* is indicated which provides for long term holding of replacement units and the transported remote equipment. The *control station* provides the operator's interface with all other elements and is, in general, remote from all of them.

A major area of interest for this study has been the work system and the technical and programmatic issues associated with its design. The effect of the other elements on the work system concept and the overall implications of different space station configurations on the design had to be considered to develop practical, useful concepts.

The following paragraphs present, first, an explanation of the development methodology followed by discussions of the major outputs resulting from its application to the concepts development process.

5.1 DEVELOPMENT OVERVIEW

The basic methodology used to define preferred system concepts for remote servicing and to establish associated space station interface requirements is described by Fig. 5-2. The approach involves the parallel development of the concepts for free flyer servicing and space station servicing with space station interfaces identified at appropriate points.

The space station base configuration will not be selected until completion of the space station Phase B studies. Therefore, the space station servicing development activity included early consideration of the potential effects of different space station configurations on the design of servicing systems.

The complete matrix of candidate approaches versus selected mission requirements is illustrated in Fig. 5-3. The four major space station configurations were considered: the CDG Planar, the Delta, the Big T and the Power Tower, which is the NASA reference concept for the Phase B studies. The study has concluded that generic worksites for the three types of servicing operations on the space station (OMV service, satellite service and assembly) can be defined for any space station configuration without significantly effecting the remote system requirements. Servicing of the space station does result in different requirements depending on the configuration. For example, servicing of body-mounted solar arrays on a Delta configuration is significantly different than servicing a rotating array on another

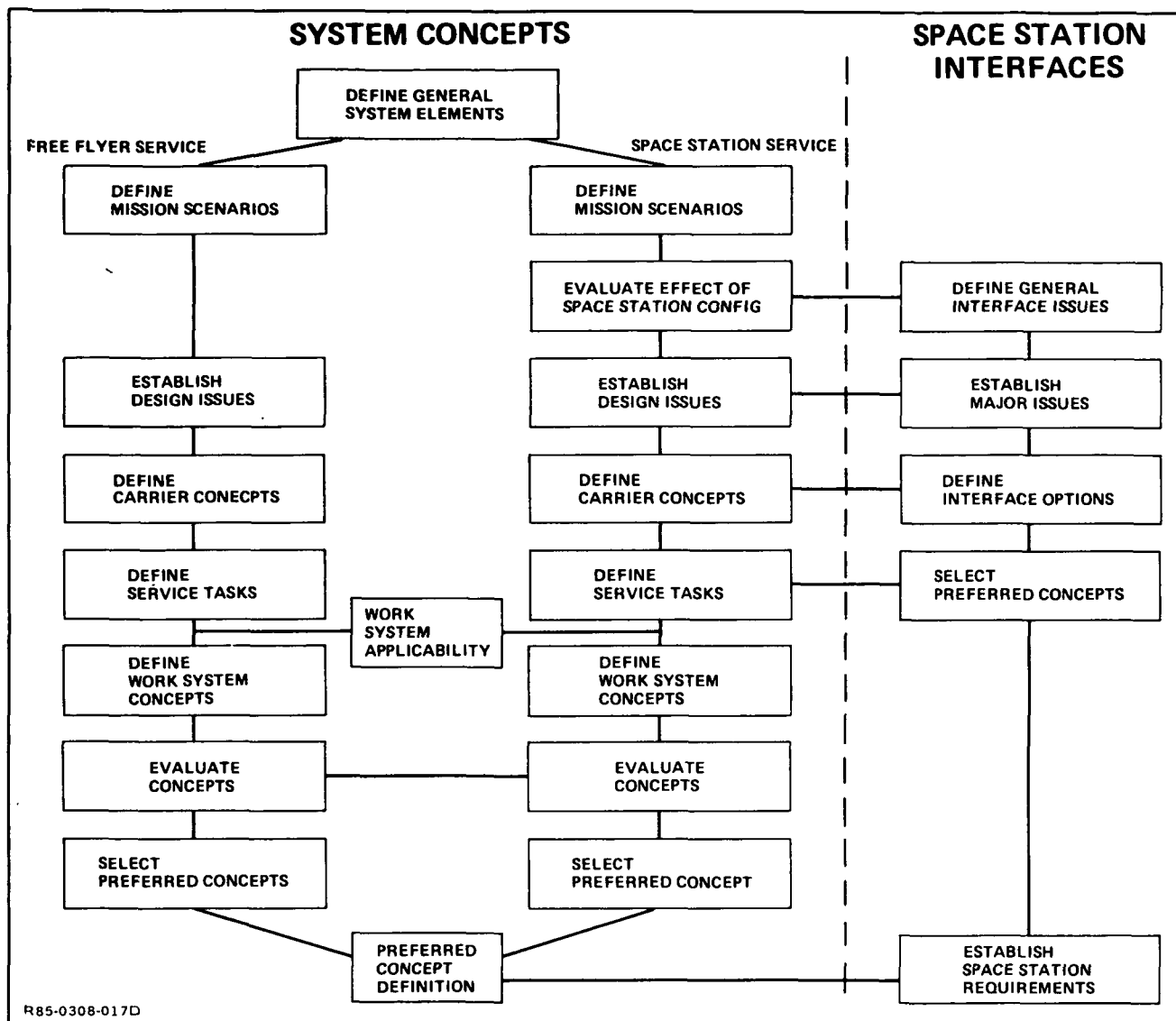


Fig. 5-2 Concepts Development Methodology

configuration. The Power Tower reference configuration was selected for more detailed analysis for the development of remote system concepts.

The free flyer servicing concepts are, of course, not effected by the space station approach as indicated.

Design issues were identified independently for the free flyer and space station servicing approaches followed by the definition of carrier concepts and specific service tasks. At this point, the applicability of candidate work system approaches,

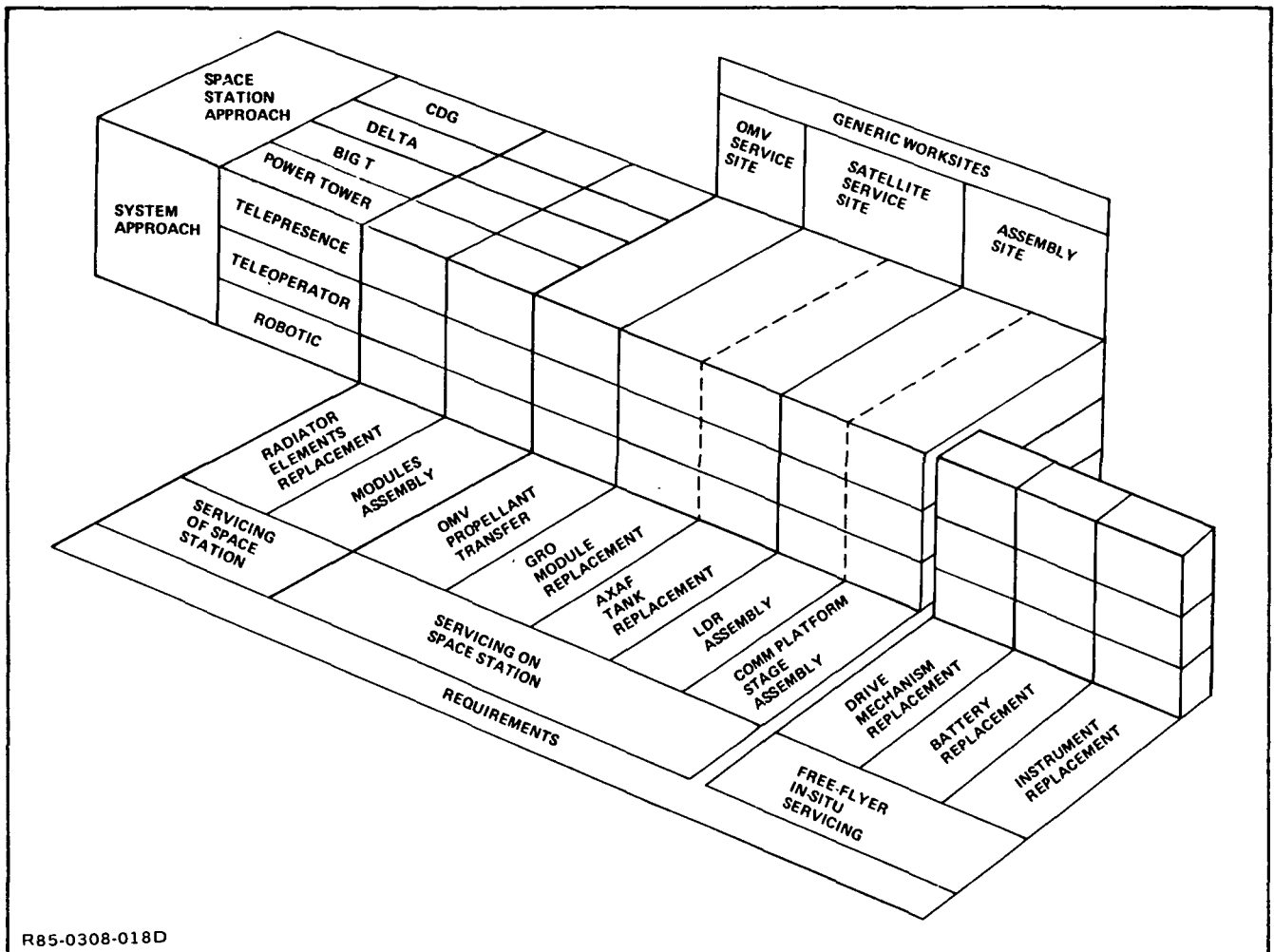


Fig. 5-3 Concepts Matrix

i.e., telepresence, teleoperator and robotic, were addressed in general terms for the full range of identified servicing tasks. These approaches are defined in Section 5.4.

Candidate work system concepts were then developed for the reference servicing missions using the appropriate design approaches. The candidate concepts were evaluated relative to mission requirements and compared to each other leading to preferred concepts for free flyer and space station servicing. The selected concepts were then developed in more detail including definition of related space station requirements.

5.2 DESIGN ISSUES

The procedures required to perform the selected servicing operations were developed to provide definition of specific remote equipment needs. Figure 5-4 illustrates the procedure for one of the servicing missions on the space station, replacement of a tank on the AXAF. Figure 5-5 illustrates a similar procedure for a free flyer servicing mission, solar array drive replacement on the SASP.

Analysis of such operational requirements were used to develop major issues associated with developing servicing concepts which are presented in Fig. 5-5. The support equipment category is generally concerned with the number and types of systems needed to bring the work system and worksite together. The work system issues, which receive major emphasis in the study, address the definition of the equipment to perform the actual servicing task.

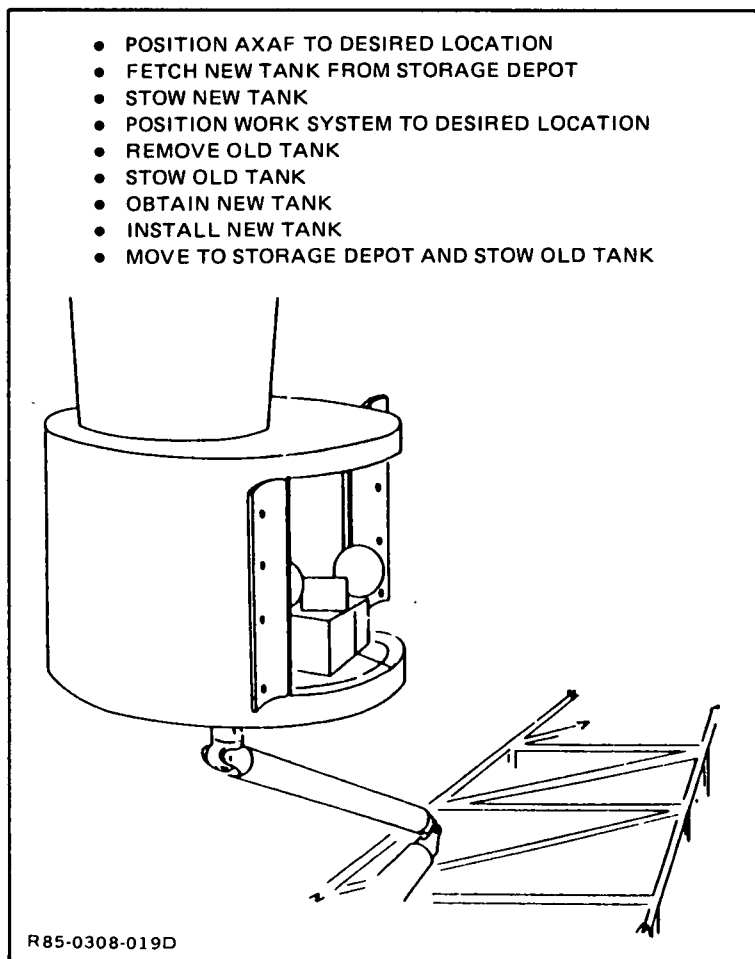


Fig. 5-4 Space Station Mission Scenario – AXAF Tank Replacement

	SPACE STATION SERVICE	FREE FLYER SERVICE
SUPPORT EQUIPMENT	<ul style="list-style-type: none"> • FIXED VS MOVABLE SERVICE EQUIPMENT • TRANSPORT SYSTEM <ul style="list-style-type: none"> – NUMBER REQUIRED – TRACK SYSTEM VS CRAWLER – SINGLE VS MULTIPLE TRACKS – HANDLING EQUIPMENT ON VS OFF – POWER TRANSFER – COMMUNICATIONS • HANDLING EQUIPMENT (TYPE, SIZE, QUANTITY) • POSITIONING ARM (TYPE, SIZE) 	<ul style="list-style-type: none"> • ATTACHMENT SYSTEM (TYPE, SIZE) • POSITIONING ARM (TYPE, SIZE)
WORK SYSTEM	<ul style="list-style-type: none"> • MANIPULATOR (SIZE, QUANTITY) • STABILIZER (SIZE, QUANTITY) • VISION SYSTEM • CONTROL TECHNIQUE 	<ul style="list-style-type: none"> • MANIPULATOR (SIZE, QUANTITY) • STABILIZER (SIZE, QUANTITY) • VISION SYSTEM • CONTROL TECHNIQUE
GENERAL	<ul style="list-style-type: none"> • UNIVERSAL VS SPECIAL DESIGNS • PARTS STORAGE • SIMULTANEOUS OPERATIONS CAPABILITY 	<ul style="list-style-type: none"> • COMMONALITY WITH SPACE STATION-BASED CONCEPTS
CONTROL STATION	<ul style="list-style-type: none"> • NO. OF OPERATORS • OPERATING VOLUME • PANEL AREA 	<ul style="list-style-type: none"> • NO. OF OPERATORS • GROUND VS SPACE STATION LOCATION
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Fig. 5-5 Design Issues

General issues are overall system concerns such as the feasibility of common designs, logistics considerations and the ability to perform different mission functions in the same timeframe. The attachment system issue for free flyer service is analogous to the handling equipment issue for space station service. Control station issues are strongly dependent on the other issues which establish functional requirements for the controls and displays and determine the operator workload.

5.3 CANDIDATE APPROACHES

The development of system concepts has considered the overall service operations on the space station. The complex nature of these operations is illustrated by the flow chart presented in Fig. 5-6 which identifies the primary activity areas on the space station. The reference mission spacecraft (AXAF, GRO, LDR and Comm Platform) are shown in the figure. Space station equipment servicing, which applies throughout the station, is not shown.

When an Orbiter arrives at the berthing area, new equipment and consumables are unloaded and failed units/debris are loaded for earth return. The cargo of Or-

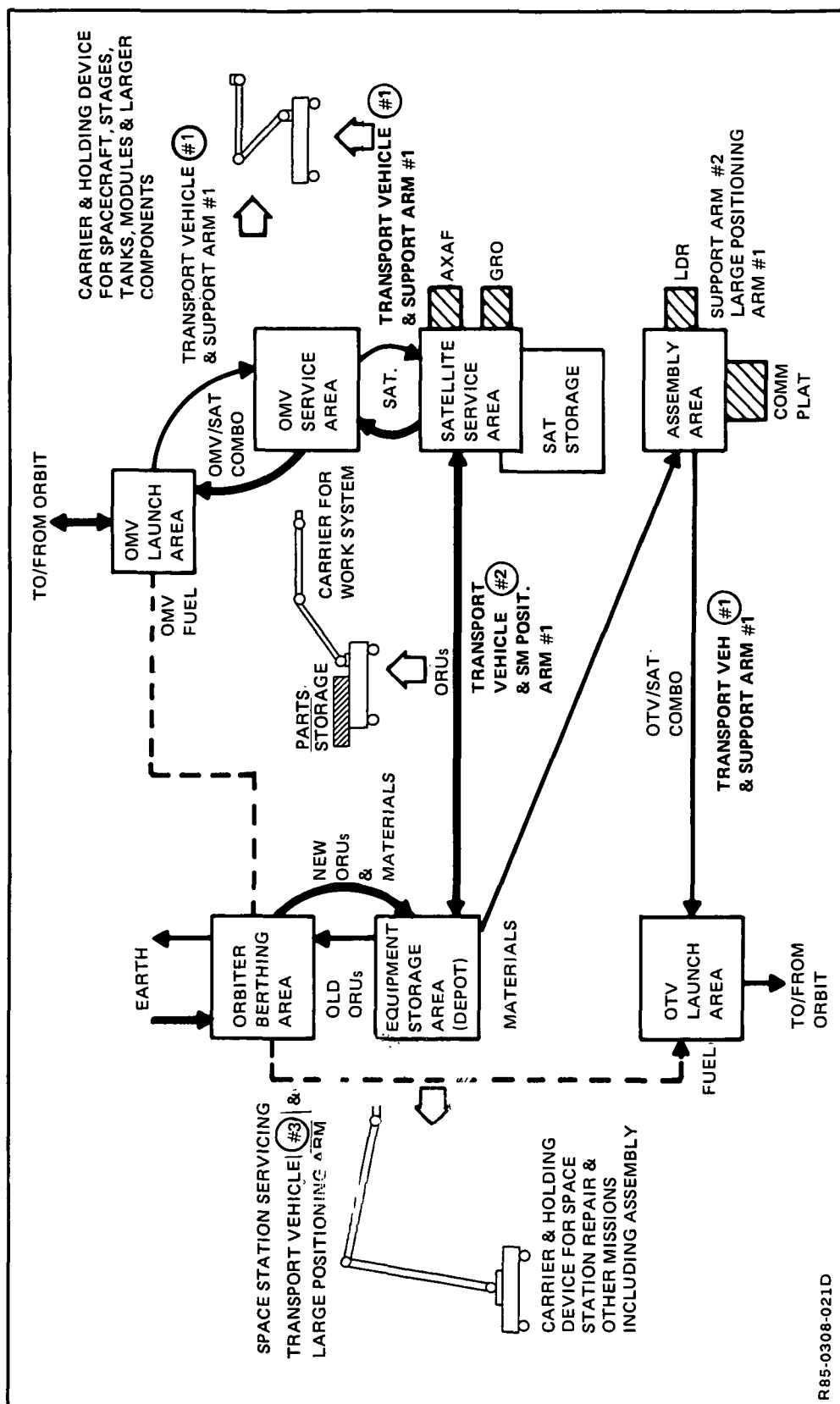


Fig. 5-6. Concepts Development - Space Station Operations Flow

bit Replacement Units (ORUs) and other materials are transferred to the storage depot and the fuel is transferred directly to the OTV and OMV launch areas. The ORUs and other materials must be subsequently brought to operational locations as required. Transport vehicles with appropriate support arms are used to reposition satellites and combinations of satellites with OTVs or OMVs between launch, service, assembly and storage areas.

Analysis of such operations has identified the need for three transport vehicles to support combined operations on the space station. As indicated in the figure, transport vehicle No. 1 carries support arm No. 1 and is used for OMV and OTV handling operations. Transport vehicle No. 2, with another positioning arm, is used for the handling and installation of ORUs and materials. For space station servicing functions, a large positioning arm on transport vehicle No. 3 is required.

The transport vehicle design can be common to all three cases as indicated in Figure 5-6, with the specific uses requiring different support and positioning arms.

In the case of free flyer servicing, the OMV provides the transport function. However, an attachment system issue was identified which is analogous to the handling equipment issue for space station servicing. The attachment system must provide a means of berthing the service vehicle to the free flyer and positioning the work system to perform servicing functions. The four basic options considered during the study to provide this capability are illustrated in Fig. 5-7. They consist of a berthing interface, with and without positioning capability, and another positioning arm for the work system. The concept's basic premise is that the OMV must be able to attach to the free flyer being serviced at a point which is in general different than the service location. The selected approach, separate arms for the berthing and work system interface, provides maximum reach and operational flexibility. The arms can be viewed as *kits* which may not be carried for every mission.

5.4 REMOTE WORK SYSTEM TYPES

Remote operating systems, as defined in this study, provide the ability to perform useful work in space at distances ranging from close proximity to thousands of miles from a human operator. The remote work system element of such systems has

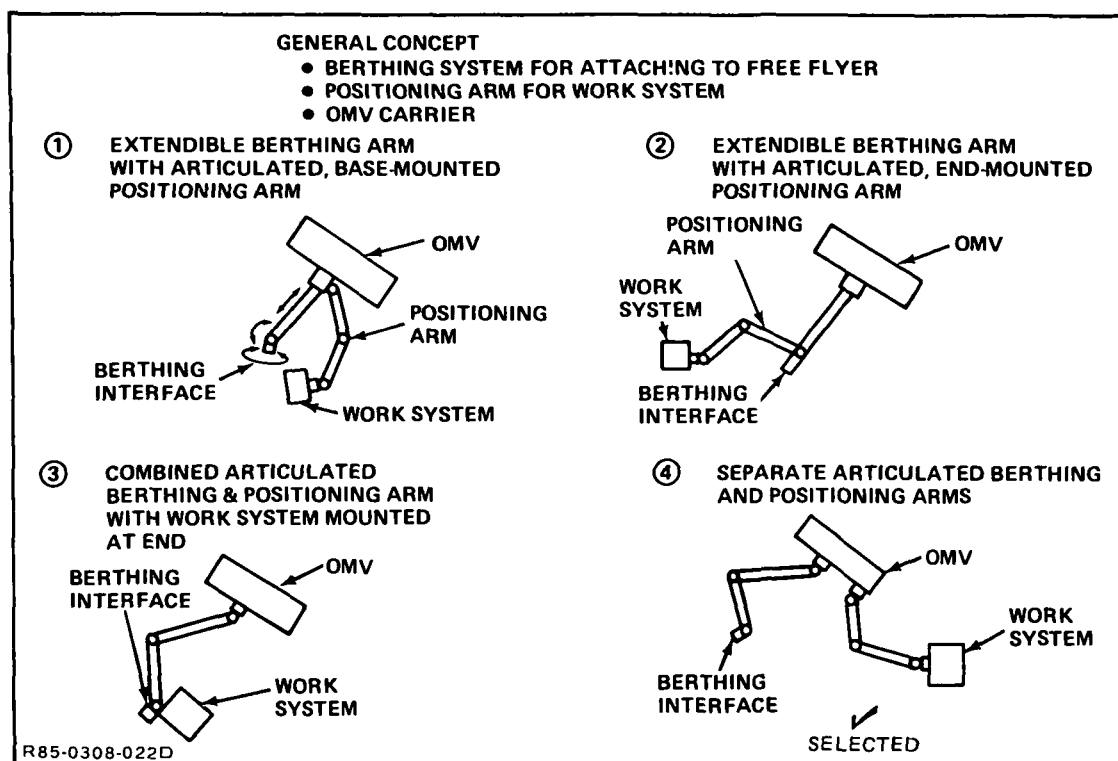


Fig. 5-7. Free Flyer Service – Berthing/ Positioning Options

been considered in terms of three general implementation approaches defined as follows:

- *Teleoperation* - This approach is the technique of human operator control of remotely located equipment which provides a basic level of real-time interaction
- *Telepresence* - This approach describes an advanced teleoperator which transfers the human's sensory perception to the remote site thereby increasing the operator's ability to interface with the task
- *Robotic* - This approach describes programmable systems which perform desired operations without direct, continuous human involvement.

A fourth approach, *Supervisory Control*, which combines the autonomous concepts of robotics with advanced teleoperator capability, offers some distinct advantages for space-based servicing operations. For the purposes of this study, we have assumed the telepresence system includes supervisory control features.

5.4.1 General Characteristics

The applicability of these approaches to particular servicing missions is a function of the characteristics of the mission tasks. The robotic approach is, in general, most suitable for missions which are described by all or most of the following characteristics:

- Lengthy procedures
- Relatively simple operations
- Repetitive operations
- Very well defined tasks
- Fully preplanned activities.

The teleoperator approach is most suitable for servicing missions which are described by:

- Relatively simple operations
- Moderately well defined tasks
- Desirability of real-time decision making.

The telepresence approach is especially suitable for:

- Complex operations
- Infrequently required tasks
- Tasks with poorly defined portions
- Tasks which require some real-time decisions.

5.4.2 Relative Capabilities

Baseline approaches for each type of remote work system, robot, teleoperator and telepresence, were established (Fig. 5-8) to assess their applicability to the variety of servicing tasks that may be encountered. The general definitions of the elements for each system are shown in the left column of the figure. In all cases it has been assumed that the system is held to the worksite by an attachment device.

The study has emphasized missions which provide maximum design features to aid remote servicing. The estimated relative difficulty experienced by each design approach is shown in the figure. Both the robotic and telepresence approach can easily perform the task. For comparison purposes, the figure also shows the estimated level of difficulty when the task has not been designed for service.

BASELINE APPROACH	APPLICABLE TASK DIFFICULTY		OPERATIONAL SPEED/ EFFECTIVENESS	SENSITIVITY TO OFF-NOMINAL CONDITIONS (CONTINGENCY)
	MINIMUM DESIGN FOR SERVICE	MAXIMUM DESIGN FOR SERVICE		
ROBOT <ul style="list-style-type: none"> • SINGLE 5 DOF ARM • FORCE/TORQUE SENSOR • VISION SYSTEM • PROGRAMMED OPERATION 	(VERY DIFFICULT TO PERFORM)	EASILY PERFORMED	FAST	HIGHLY SENSITIVE
TELEOPERATOR <ul style="list-style-type: none"> • SINGLE 6 DOF ARM • RESOLVED RATE CONTROL • FORCE/TORQUE SENSOR • MONO VIDEO • SIMPLE GRAPHICS 	(VERY DIFFICULT TO PERFORM)	PERFORMED WITH SOME DIFFICULTY	SLOW	MODERATELY SENSITIVE
TELEPRESENCE <ul style="list-style-type: none"> • TWO 7 DOF ARMS • REPLICA CONTROL • FORCE FEEDBACK* • STEREO VIDEO • ADVANCED GRAPHICS 	(PERFORMED WITH SOME DIFFICULTY)	EASILY PERFORMED	MODERATE	RELATIVELY INSENSITIVE
*ONLY WITHOUT TIME DELAY (I.E., ON SPACE STATION) R85-0308-023D				

Fig. 5-8 Concepts Development – Remote Work Systems Assessment

The two key performance measures assessed are operational speed and the sensitivity to off-nominal, unplanned conditions. The robotic system has the advantage of speed but is highly sensitive to contingency situations which require unplanned operations. The telepresence approach is comparatively insensitive to such off-nominal conditions but is generally slower than the robot. The teleoperation approach generally exhibits performance that is slow but with some capability to handle contingency operations.

5.4.3 Mission Applications

Such considerations of the characteristics/limitations of each approach combined with the functional analysis of each service task were used to select the appropriate approaches for each mission presented in Fig. 5-9. The goal was to select the simplest acceptable approach for each application where the robotic approach is considered the simplest and telepresence is the most complex.

In some cases, e.g., battery replacement on SASP, a single approach (robotic) was considered most applicable but, in general, the choice was not clear cut and two were selected. The two-arm telepresence approach can perform all tasks but is too sophisticated in some cases even when contingency operations are considered. In

		ROBOT	TELEOPERATOR	TELEPRESENCE
SERVICING ON SPACE STATION	• RADIATOR PANEL REPAIR	✓	✓	
	• LOGISTICS MODULE INSTALLATION		✓	✓
	• OMV PROPELLANT TRANSFER	✓	✓	✓
	• AXAF TANK REPLACEMENT		✓	✓
	• LDR ASSEMBLY		✓	✓
	• COMM PLATFORMS/STAGE ASSEMBLY		✓	
	• GRO SUBSYSTEM MODULE REPLACEMENT	✓	✓	
IN-SITU SERVICING (SASP)	• DRIVE MECHANISM REPLACEMENT		✓	✓
	• BATTERY REPLACEMENT	✓		
	• INSTRUMENTS/MANUFACTURED PRODUCTS REPLACEMENT			✓
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Fig. 5-9 Concepts Development – Selected Remote Work System Applications

the case of a highly variable mission, such as replacement of instruments and manufactured products in a wide range of payload equipment, telepresence is the preferred approach.

5.5 REMOTE OPERATING SYSTEM CONCEPTS

Each servicing mission was analyzed using computer graphics (Fig. 5-10) to establish the minimum manipulator arm lengths and degrees of freedom (DOF) required to perform the specific operations. A four foot manipulator length requirement resulted with five to seven DOF required, depending on the task. The analysis also showed that an eight foot, 6 DOF stabilizer (attachment system) is required for the work system.

In addition to the definition of the work system manipulators, the analysis also established requirements for other remote operating system elements. A 26 foot positioning arm with 7 DOF is required to orient the work system properly relative to the worksite and move it to obtain replacement units and other materials. In addition, a need was identified (Fig. 5-11) for a similar positioning arm for servicing of a free flyer by a remote work system carried by an OMV. Such an arm would provide the necessary reach for positioning the work system when the OMV is attached to a free flyer. In some cases, a second such arm may be required for servicing a large free flyer, such as a platform, for berthing the OMV and for providing the necessary reach to particular locations on the spacecraft. This second positioning arm could be a permanent part of the platform.

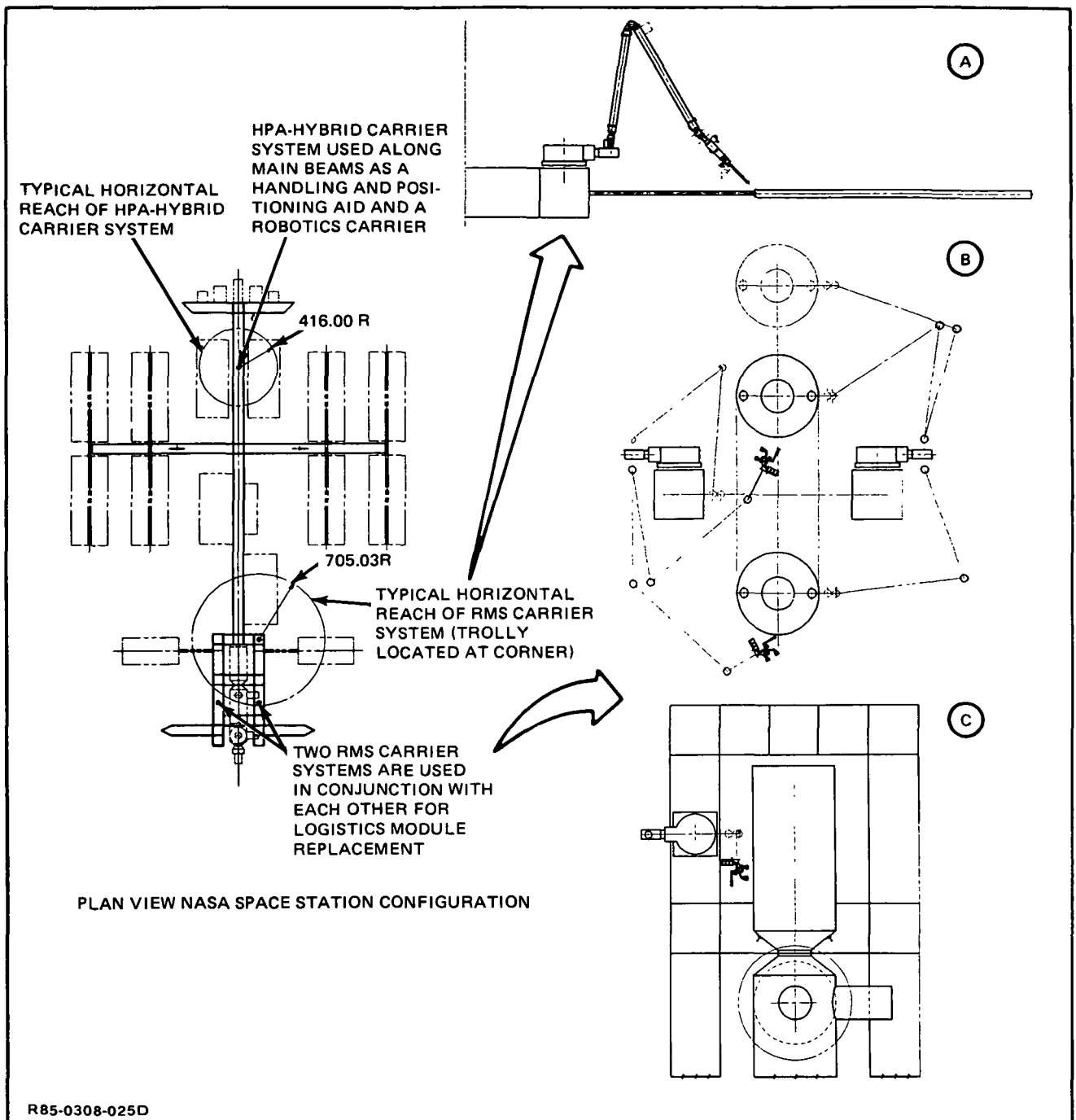


Fig. 5-10 Space Station Transport Vehicle Requirements

The selected Remote Operating System concept for servicing on the space station is illustrated in Fig. 5-12 which shows an AXAF-type spacecraft being serviced by a telepresence-type work system. Replacement units are shown in an enclosed storage rack on the carrier vehicle. Operation of the remote system is under the control of an operator in a habitation module located elsewhere on the space station.

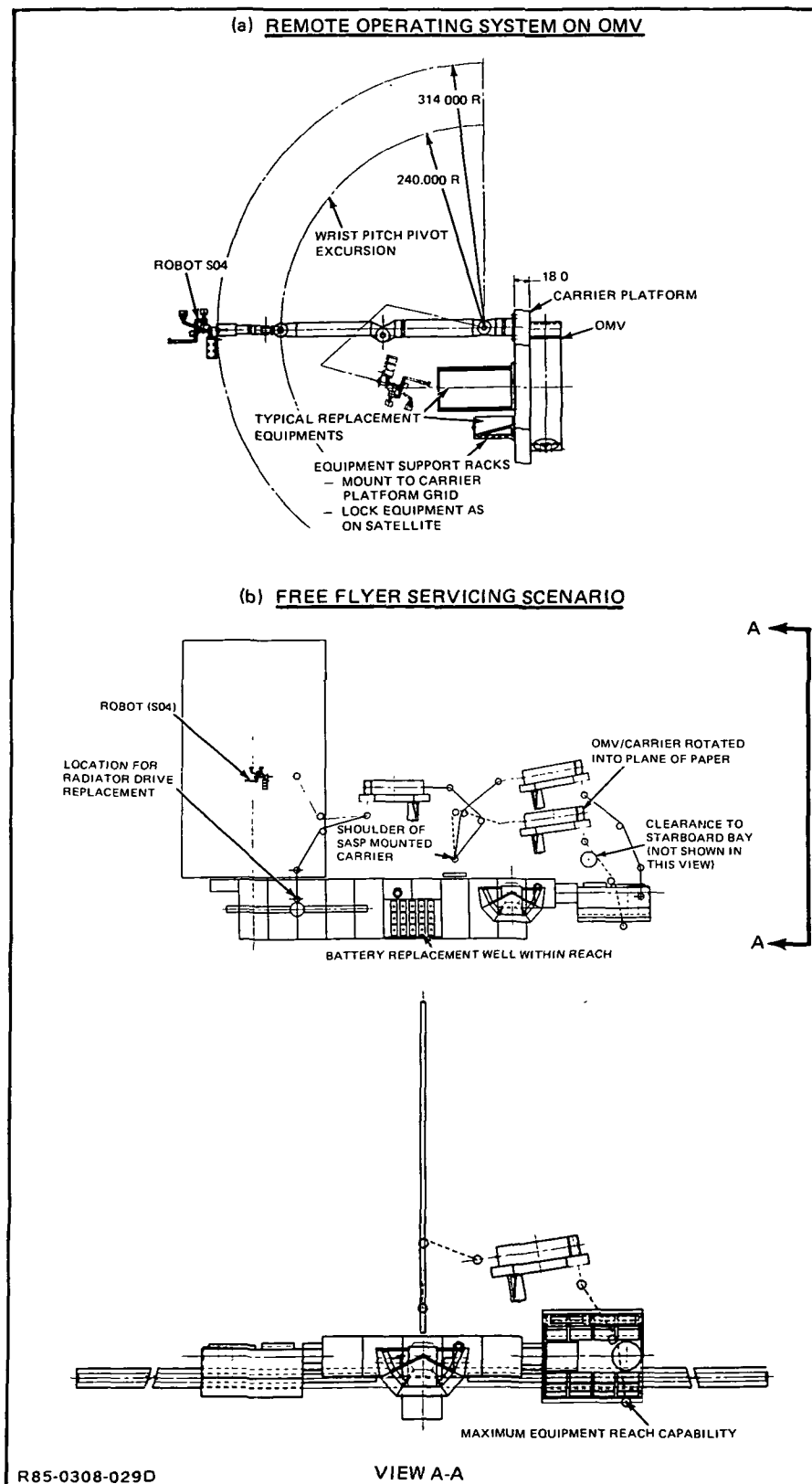


Fig. 5-11 Free Flyer Servicing

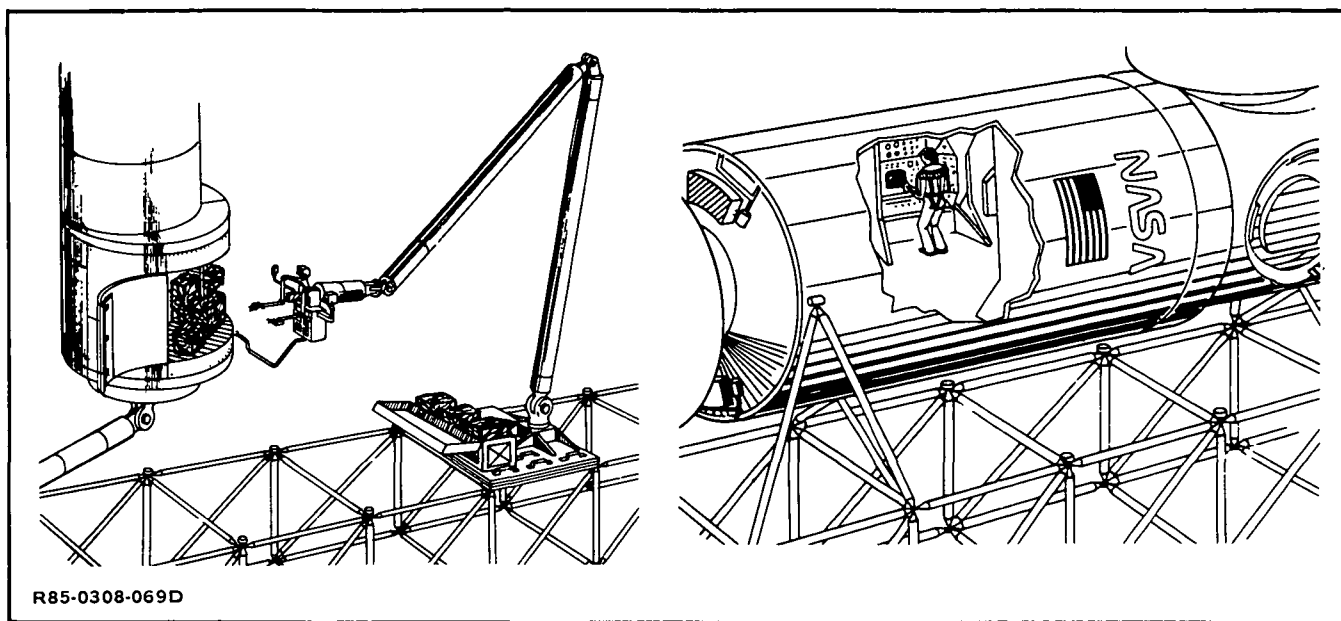


Fig. 5-12 System Concept — Service on Space Station

The concept for free flyer servicing is illustrated in Fig. 5-13. The telepresence work system is mounted to a positioning arm with two replacement units mounted to a storage rack on the carrier vehicle.

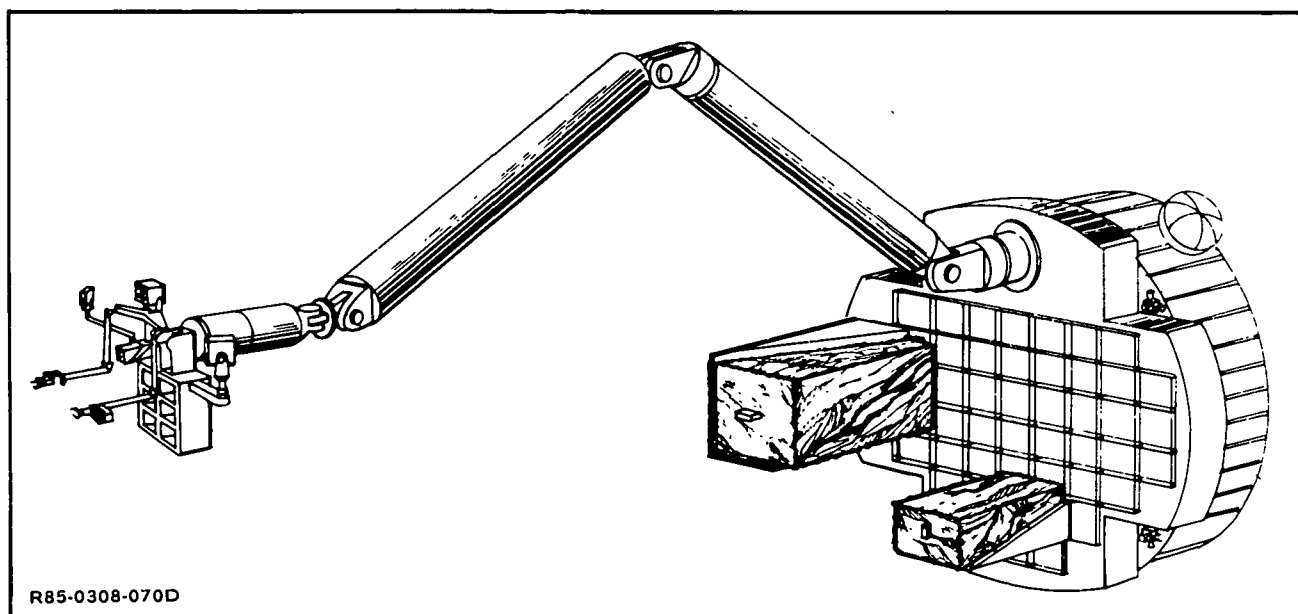


Fig. 5-13 System Concept — Free Flyer Service

5.6 REMOTE WORK SYSTEM CONCEPTS

The remote work system concepts were developed using an iterative computer-aided design procedure which is illustrated in Fig. 5-14. Candidate manipulator physical configurations were established based on general mission requirements.

Integrated concepts, including lights, TV cameras and attachment systems, were then developed around these manipulator systems. The integrated concepts were then applied to the mission scenarios to determine feasibility and relative performance.

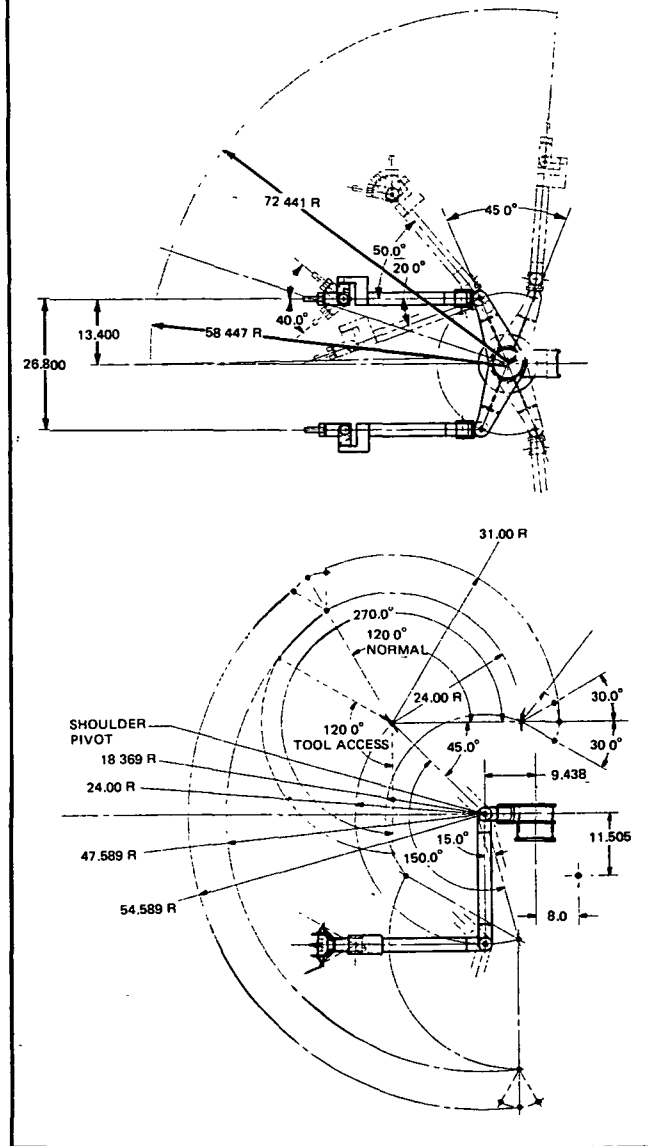
The resulting selected work system design concepts are illustrated in Fig. 5-15 through 17. The robotic concept (Fig. 5-15) consists of a single programmable 5 DOF manipulator and a robot vision system mounted to a base structure which contains the control electronics. A CCTV camera (not shown) is provided as a means of monitoring task performance. The attachment system which is mounted to the bottom of the structure is the same for each work system concept. Alternate general purpose and mission-unique end effectors are stowed in compartments on either side of the base structure. Power, commands and data interfaces are provided through the attachment fitting on the positioning arm.

The teleoperator work system (Fig. 5-16) consists of a single 6 DOF manipulator in an anthropomorphic configuration mounted to a shoulder assembly. Two CCTV cameras are shown, one located above and in front of the primary work zone. Another CCTV camera is mounted on an outrigger arm providing a line of sight about 45 deg from the centerline at the primary work zone. A rack of alternate end effectors is mounted to the front of the control electronics assembly which forms the main structure.

The telepresence work system (Fig. 5-17) is composed of two 7 DOF dexterous manipulators in an anthropomorphic configuration combined with a stereo vision system mounted to a pivoting shoulder assembly. In addition, there are right and left cameras mounted on positioning arms and a central belly camera. The main structure contains the control electronics with alternate end effectors stored in compartments in front.

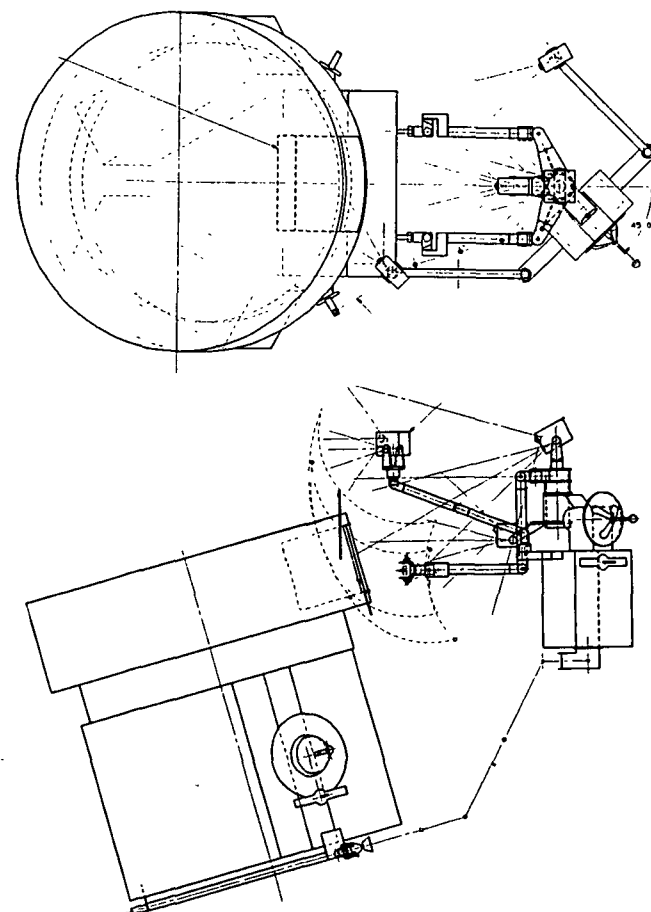
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MANIPULATOR GEOMETRY & REACH



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SERVICING SCENARIO



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INTEGRATED REMOTE WORK SYSTEM CONCEPT (TELEPRESENCE)

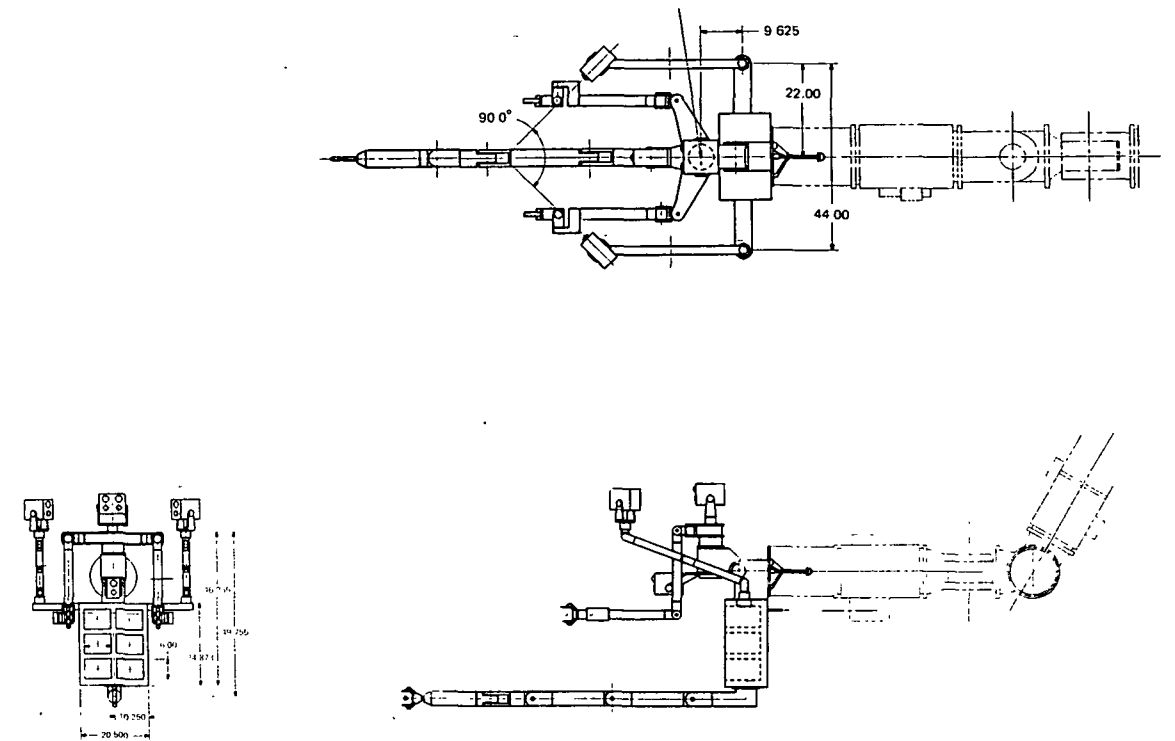


Fig. 5-14 Iterative Concept Design Procedure (Example)

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2 FOLDCUT FRAME

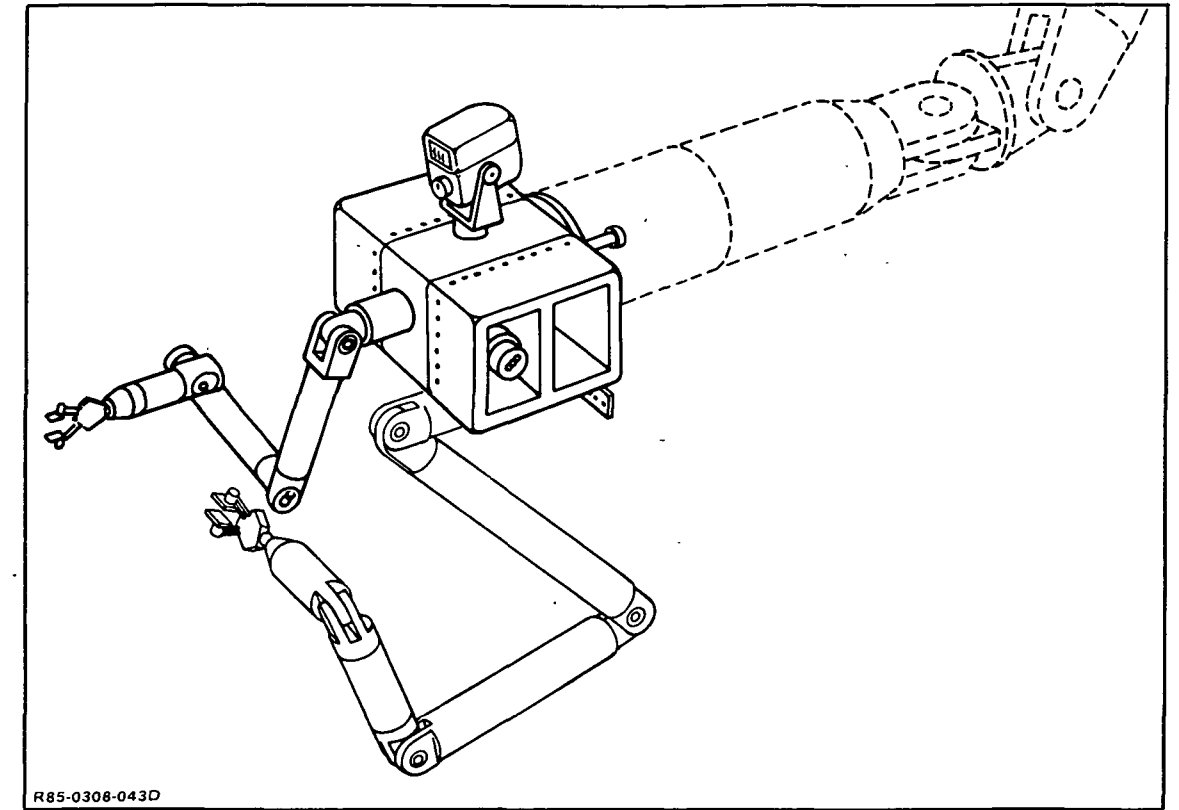


Fig. 5-15 Robotic Work System Concept

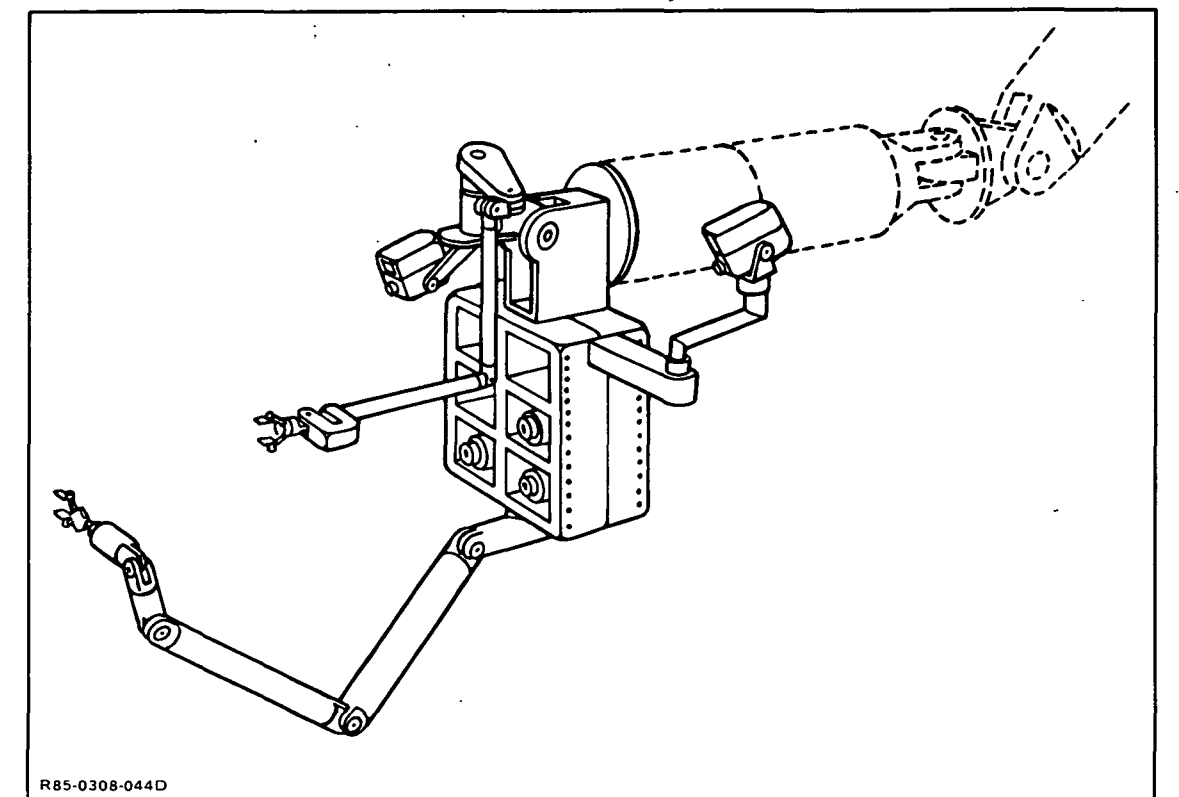


Fig. 5-16 Teleoperator Work System Concept

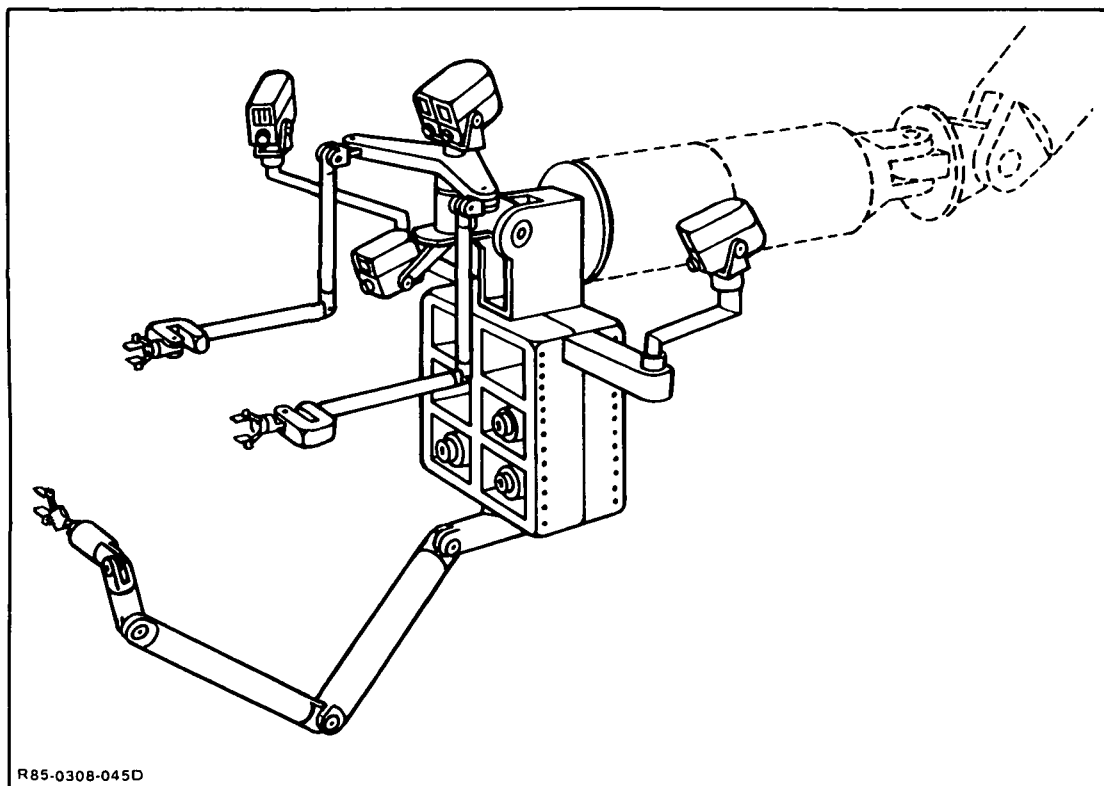


Fig. 5-17 Telepresence Work System Concept

The estimated weights of the three work system concepts are presented in Fig. 5-18.

The design requirements for each subsystem of the telepresence remote work system are presented in Fig. 5-19. The check-out subsystem requirements are not specified because they are concept and mission dependent. The requirements specified for the other subsystems collectively describe an overall performance capability which meets a wide range of mission applications.

5.7 SPACE STATION INTERFACES

The major interfaces of the space station-based remote operating systems with the space station are established from the functional requirements including:

- Mobility to and from worksites
- Secure attachment
- Accessibility for servicing

- Crew accommodations to support operations
- Subsystem support (power, comm, etc)
- Outfitting and storage provisions.

The interface requirements for the major remote operating system elements are as follows:

Transport Vehicle

- Provide guides for vehicle support and mobility
- Provide mechanical locomotion
- Provide electrical power, communications, and data handling.

Remote Work System

- Provide storage provisions
- Provide utilities support.

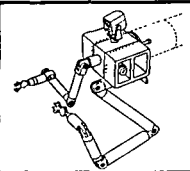
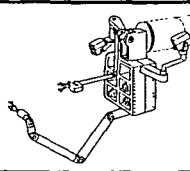
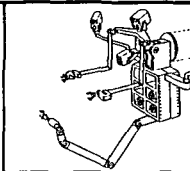
			
WORK SYSTEM ELEMENT	ROBOTIC SYSTEM	TELEOPERATOR SYSTEM	TELEPRESENCE SYSTEM
ATTACHMENT SYSTEM (STABILIZER)	40	40	40
MANIPULATOR(S)	175	115	215
VISION SYSTEM	26	35	22
LIGHTING SYSTEM	10	10	10
CHECKOUT SYSTEM	30	30	30
CONTROL ELECTRONICS STRUCTURE	100 57	60 44	80 60
TOTAL (LB)	438	334	457
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Fig. 5-18 Work System Weight Estimates

SUBSYSTEM	REQUIREMENTS (PER SYSTEM)	REQUIREMENT VALUE
ATTACHMENT SUBSYSTEM (MECHANICAL DEVICES FOR POSITIONING & STABILIZING THE REMOTE WORK SYSTEM WITH RESPECT TO THE WORK SITE)	<ul style="list-style-type: none"> • QUANTITY • SIZE • NUMBER OF SEGMENTS • DOF • MAX TIP SPEED • MAX TIP FORCE • MAX TIP TORQUE • OPERATING VOLUME • END EFFECTOR TYPE(S) • END EFFECTORS, QUANTITY • END EFFECTOR DOF 	1 8 FT 5 6 6 IN/SEC 100 LBF 40 IN-LB 2000 FT ³ TONG & MINI-GRAPPLER 2 1
MANIPULATOR SUBSYSTEM ELEMENT (ELECTRO-MECHANICAL DEVICES FOR HOLDING & MOVING TOOLS, EQUIPMENT & MATERIALS)	<ul style="list-style-type: none"> • QUANTITY • SIZE • DOF • MAX TIP SPEED • MAX FORCE • MAX TORQUE • OPERATING VOLUME • END EFFECTOR TYPES (INCLUDING TOOLS) • END EFFECTORS, QUANTITY • END EFFECTORS, DOF 	2 4 FT 7 24 IN/SEC 20 LBF 10 IN-LB 275 FT ³ VARIOUS MISSION DEPENDENT 3 1
VISION SUBSYSTEM ELEMENT (ELECTRO-OPTICAL DEVICES TO PROVIDE VISUAL INFOR- MATION ABOUT THE WORKSITE)	<ul style="list-style-type: none"> • QUANTITY • INSTANTANEOUS COVERAGE ANGLE • TOTAL COVERAGE • SENSOR TYPE • DIMENSION • RESOLUTION • SENSITIVITY • PAN RATE • TILT RATE • ZOOM TIME • ZOOM RANGE (MAX) 	5 (2 IN STEREO CONFIGURATION) 45 DEG SPHERICAL CCD 30 IN ³ 180 K PICELS 5. FT-LAMBERTS 0 TO 10 DEG/SEC (VARIABLE) 0 TO 5 DEG/SEC (VARIABLE) 10 SEC SEL. 10:1
LIGHTING SUBSYSTEM (EQUIPMENT TO ILLUMINATE THE WORKSITE)	<ul style="list-style-type: none"> • COVERAGE ANGLE • INTENSITY RANGE • CONTROL MODE 	90 DEG VARIABLE AUTOMATIC
CHECKOUT SUBSYSTEM (EQUIPMENT TO TEST THE OPERATION OF SERVICED UNITS)	<ul style="list-style-type: none"> • FUNCTIONS • MECHANICAL INTERFACES • ELECTRICAL INTERFACES 	VARIABLE PROGRAM STND & SPECIAL PURPOSE STND & SPECIAL PURPOSE
CONTROL ELECTRONICS SUBSYSTEM (ELECTRONIC UNIT TO MONITOR AND CONTROL THE OTHER ELEMENTS)	<ul style="list-style-type: none"> • MISSION FUNCTIONS • HOUSEKEEPING FUNCTIONS • ELECTRICAL INTERFACES 	N/A N/A N/A
STRUCTURE/STORAGE SUBSYSTEM (PROVIDE STRUCTURAL SUPPORT FOR OTHER ELEMENTS, STORAGE FOR END EFFECTORS & MOUNTING INTERFACE)	<ul style="list-style-type: none"> • SIZE • ATTACHMENTS, QUANTITY • ATTACHMENTS, SIZE RANGE • MOUNTING INTERFACE 	CONCEPT DEPENDENT CONCEPT DEPENDENT CONCEPT DEPENDENT STANDARD RMS GRAPPLE FITTING

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Fig. 5-19 Remote Work Systems – Requirements Summary

Handling Equipment

- Provide mechanical mounting
- Provide power, communications, and data handling.

Storage Facility (Depot)

- Provide mechanical mounting
- Provide thermal control
- Provide instrumentation.

Control Station

- Provide controls and displays for operating other elements
- Monitor performance of other elements.

A number of major interface issues were identified. Figure 5-20 lists these issues and provides a selected design option for each based on consideration of advantages and disadvantages.

A mobile remote operating system controlled either from the space station or the ground is selected as the most flexible operational concept. More than two different remote operating systems are chosen to provide maximum servicing capability. The ability to position both the work system and the payload being worked on (when possible) is selected for optimum access. A distributed power source is chosen to provide servicing operations without time limitations or restrictions. A simple wired communications system is chosen as a secure, unrestricted link. A storage depot is recommended for logistics support to provide maximum operational capability.

Figure 5-21 is a general block diagram for a remote operating system on the space station. The signal and power flow between all major elements of the system is shown. For the selected concept, all interfaces with the space station are via the transport vehicle of the remote operating system.

Space station control station concepts for remote systems operations were developed via computer aided design for one and two operator concepts as illustrated in Fig. 5-22.

FOLDOUT FRAME

2 FOLDOUT FRAME

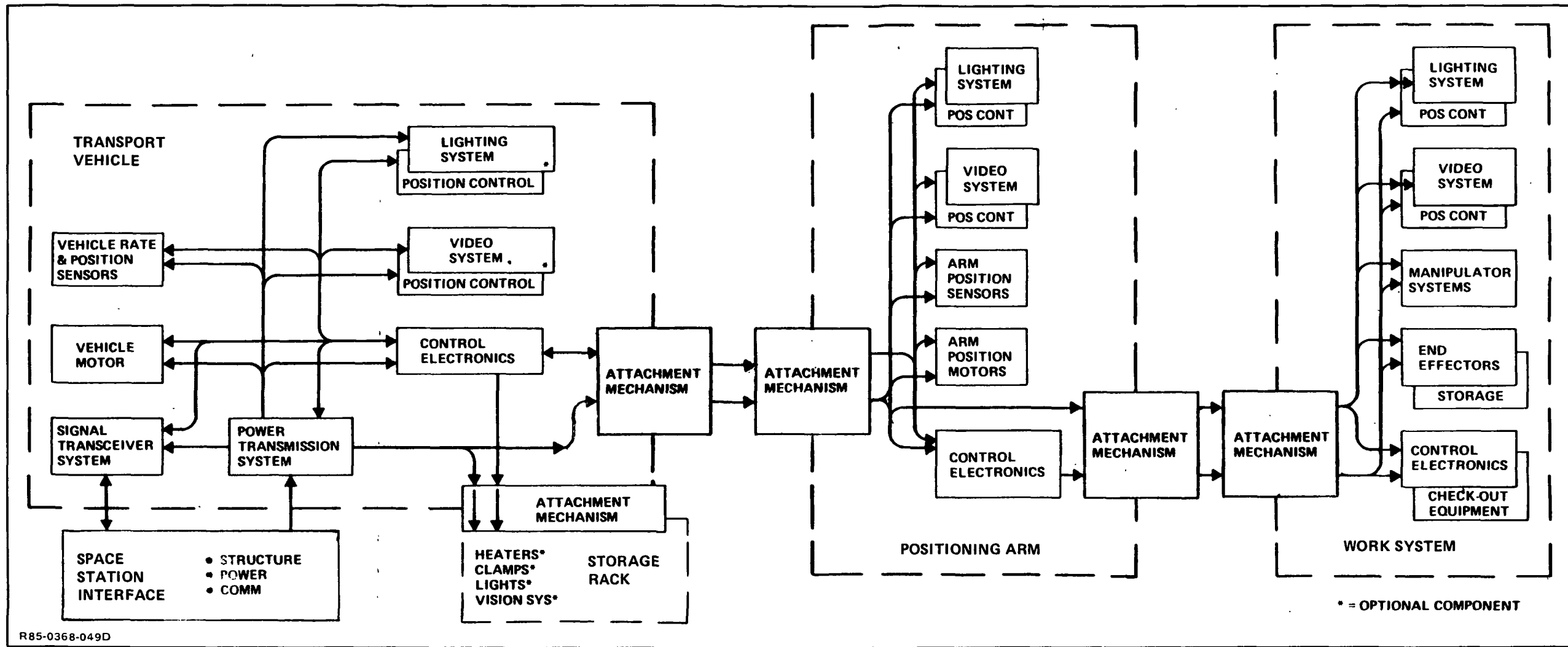


Fig. 5-21 Space Station Remote Operating System — Block Diagram

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INTERFACE ISSUE	DESIGN OPTIONS	SELECTED OPTION	ADVANTAGES	DISADVANTAGES
REMOTE OPERATING SYSTEM LOCATION	FIXED-DIRECT VIEW		NATURAL VIEWING	UNIQUE VIEWING CONDITIONS REQD
	FIXED-INDIRECT VIEW		OPTIMUM SYSTEM CONFIG POSSIBLE	PAYLOADS TRANSPORT TO WORKSITE
	MOBILE	✓	REPAIR IN PLACE, MULTIPLE SYSTEMS POSS	TRANSPORT SYSTEM(S) REQD PLUS SUPPORT
CONTROL STATION LOCATION	SPACE STATION		NO TIME DELAY; CREW UTILIZATION	CREW AVAILABILITY & TRAINING
	GROUND		EXPERTS UTILIZATION	TIME DELAY ENVIRONMENT
	SPACE STATION/ GROUND COMB.	✓	AVOID TIME DELAY WHERE SIGNIFICANT; REDUNDANCY	DUPLICATION; PROTOCOL ISSUES
REMOTE OPERATING SYSTEMS QUANTITY	ONE		LOWER TOTAL COST	MORE GENERAL REQMTS
	TWO (SAME)		MULTIPLE MISSIONS CAPABILITY; SPARES	HIGHER COSTS
	TWO (DIFFERENT)		MULTIPLE MISSIONS; EFFICIENT OPS	HIGHER COSTS, INCREASED SYSTEM COMPLEXITY
	MORE THAN TWO (SAME)		HIGHER UTILIZATION	HIGHER COST & COMPLEXITY
	MORE THAN TWO (DIFFERENT)	✓	HIGHER UTILIZATION, MORE EFFICIENT	HIGHER COST & COMPLEXITY
ACCESS PROVISIONS	POSITION WORK SYSTEM OR POSITION PAYLOAD		FEWER POSITIONING SYSTEMS REQD	LARGER, MORE COMPLEX POSITIONING SYSTEM
	POSITION WORK SYSTEM & POSITION PAYLOAD	✓	OPTIMUM POSITIONING POSSIBLE	MULTIPLE POSITIONING SYSTEMS REQD
POWER SOURCE	STORED		SELF CONTAINED, RELATIVELY SIMPLE	HEAVY, RECHARGE TIME LIMITATIONS
	DISTRIBUTED	✓	NOT TIME LIMITED, LOWER SYSTEM WEIGHT	MORE COMPLEX, IMPACTS SPACE STATION SYSTEMS
COMMUNICATIONS APPROACH	RF		MINIMUM MECH IMPACT, HIGH BANDWIDTH	LINE-OF-SIGHT RESTRICTIONS
	WIRED	✓	DIRECT, SECURE LINK	ADDED COMPLEXITY, POSS NOISE SUSCEPT.
STORAGE PROVISIONS (SYSTEMS & PARTS)	STORAGE DEPOT	✓	AVAIL. OF POTENTIAL REPLACEMENT UNITS	ADDED REQMT & CONFIG EFFECTS
	NONE		REDUCED IMPACT ON SPACE STATION CONFIGURATION	ORBITER SUPPLY REQD & INVENTORY CONTROL

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Fig. 5-20 Space Station Interface Options

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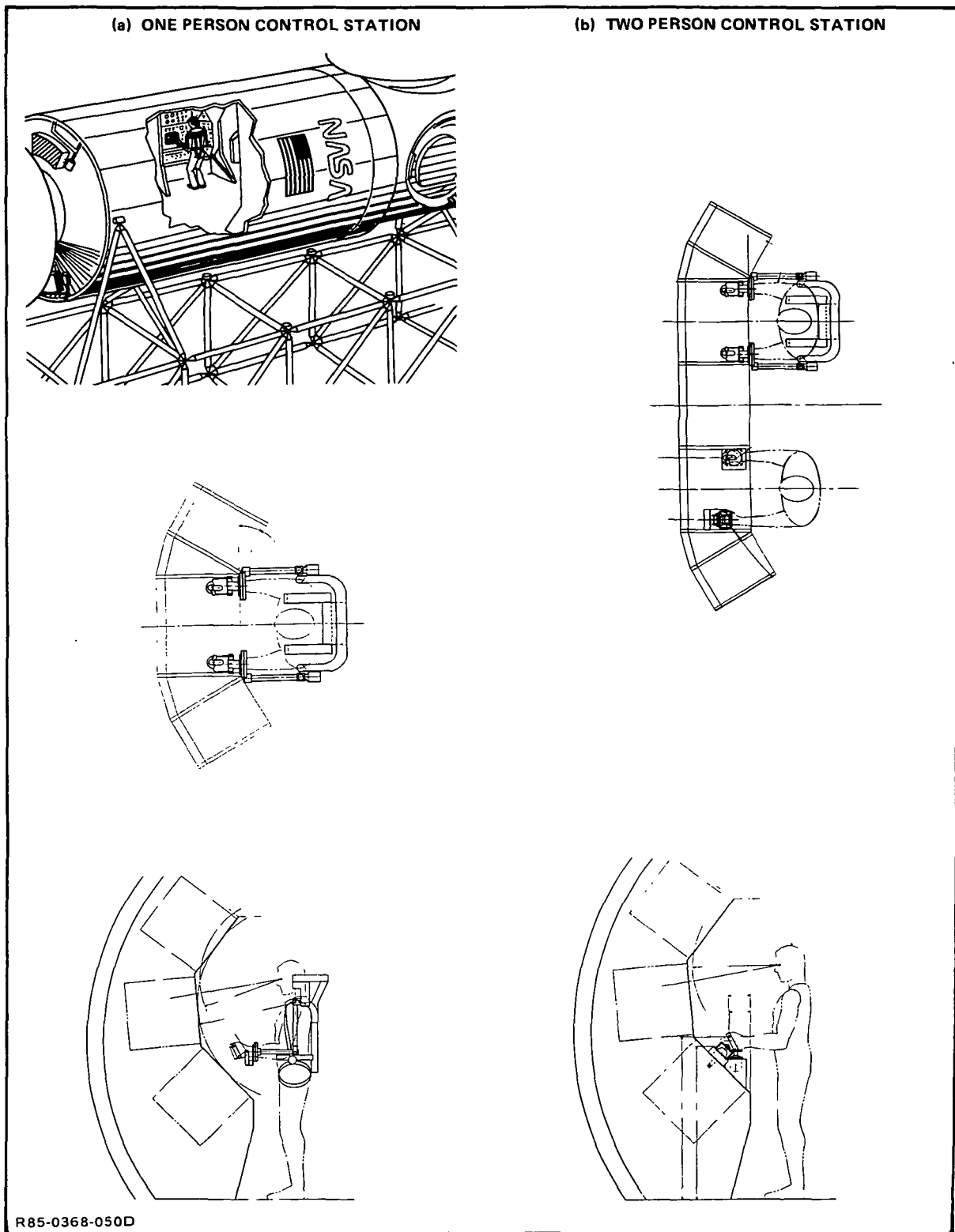


Fig. 5-22 Control Station Concepts

5.8 SYSTEM DEVELOPMENT PROGRAM

Programmatic concepts for the development of remote operating systems technology and operational capability have been defined. The primary study products consist of an assessment of technology readiness, a development plan and an estimate of program costs for the remote work system.

5.8.1 Technology Readiness Assessment

Review of the current (July 1984) program schedules for the space station and the OMV identified a need for operational remote operating systems capability by early 1991.

The five major elements necessary to implement such remote operations were evaluated (Fig. 5-23) in terms of their current levels of technology development. The transport vehicle and the work system were identified for development emphasis because of their moderate to high levels of schedule and technical risk.

The work system, which was the highest technology risk item, was evaluated (Fig. 5-24) to establish subsystem elements which require development priority. The eight numerical levels of technology readiness define major steps in the development of an operational system. Five key technology development areas were identified for the moderate and high risk subsystems:

ELEMENT	CURRENT TECHNOLOGY STATUS	SCHEDULE RISK	TECHNICAL RISK
TRANSPORT VEHICLE	EARLY CONCEPTS FORMULATED	HIGH	MODERATE*
POSITIONING ARM/ HANDLING DEVICE	• LARGE ARM (RMS) OPERATIONAL-MODS REQD • SMALL ARM DEVEL TEST ARTICLE-MODS REQD	LOW	LOW
WORK SYSTEM	• CONCEPTS FORMULATED • CRITICAL HARDWARE UNDER DEVELOPMENT	MODERATE	HIGH*
STORAGE RACK	EARLY CONCEPTS FORMULATED	MODERATE	LOW
CONTROL STATION	LIMITED TESTING OF CONCEPTUAL DESIGNS	LOW	MODERATE
*ELEMENTS CALLING FOR DEVELOPMENT EMPHASIS			
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Fig. 5-23 Technology Risk Assessment

SUBSYSTEM	CRITICAL TECHNOLOGY ITEMS	CURRENT READINESS LEVEL	DEVELOPMENT RISK
ATTACHMENT SYSTEM	• MECHANICAL ARMS	3	LOW
	• END EFFECTORS	2	
	• CONTROL SYSTEM*	3	
MANIPULATORS	• MECHANICAL ARMS	2	HIGH
	• END EFFECTORS/TOOLS	3	
	• INSTRUMENTATION	3	
	• CONTROL SYSTEM*	2	
VISION SYSTEM	• SENSORS	7	MODERATE
	• POINTING SYSTEM	3	
	• CONTROL SYSTEM*	2	
LIGHTING SYSTEM	• LIGHT SOURCES	7	LOW
	• POINTING SYSTEM	2	
	• CONTROL SYSTEM*	2	
CHECKOUT SYSTEM	• AUTOMATED TEST	1	MODERATE
	• SERVICE FUNCTIONS	3	
	• SUBSYSTEM INTERFACES	3	
CONTROL ELECTRONICS	• CONTROL SYSTEM	3	HIGH
	• SIGNAL PROCESSING	3	
	• MODE CONTROL	2	
STORAGE SYSTEM/ MOUNTING STRUCTURE	• STRUCTURE	2	LOW
	• THERMAL CONTROL	2	
	• CONTROL SYSTEM*	2	
CONTROL STATION,	• MANIPULATOR CONTROLS	3	HIGH
	• VISION SYSTEM DISPLAY	3	
	• SYSTEM MONITOR	2	

*FUNCTION CENTRALIZED IN CONTROL ELECTRONICS

Legend: Technology Rediness Levels:

LEVEL 1:	BASIC PRINCIPLES OBSERVED AND REPORTED	TECHNOLOGY DEVELOPMENT
LEVEL 2:	CONCEPTUAL DESIGN FORMULATED	
LEVEL 3:	CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY	
LEVEL 4:	CRITICAL FUNCTION/CHARACTERISTIC DEMONSTRATED	ADVANCED DEVELOPMENT
LEVEL 5:	COMPONENT/BRASSBOARD TESTED IN RELEVANT ENVIRONMENT	
LEVEL 6:	PROTOTYPE/ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT	
LEVEL 7:	ENGINEERING MODEL TESTED IN SPACE	OPERATIONS
LEVEL 8:	BASELINED INTO PRODUCTION DESIGN	

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Fig. 5-24 Remote Work System Technology

- Space-qualified dexterous manipulators with interchangeable end effectors
- Effective vision systems for remotely operated and automated systems
- Flexible checkout system design for a wide range of mission applications
- Control systems for complex electromechanical systems including time delay effects
- Operator-machine interface for optimum system performance.

The overall technology readiness level is estimated to be between the two and three level.

5.8.2 Technology Development Program

A development program schedule for the remote work systems was defined (Fig. 5-25) which is keyed to the major milestones of the space station program in addition to providing OMV servicing capability in 1991. The program projects progressive increases in the technology readiness level with some of the major elements already

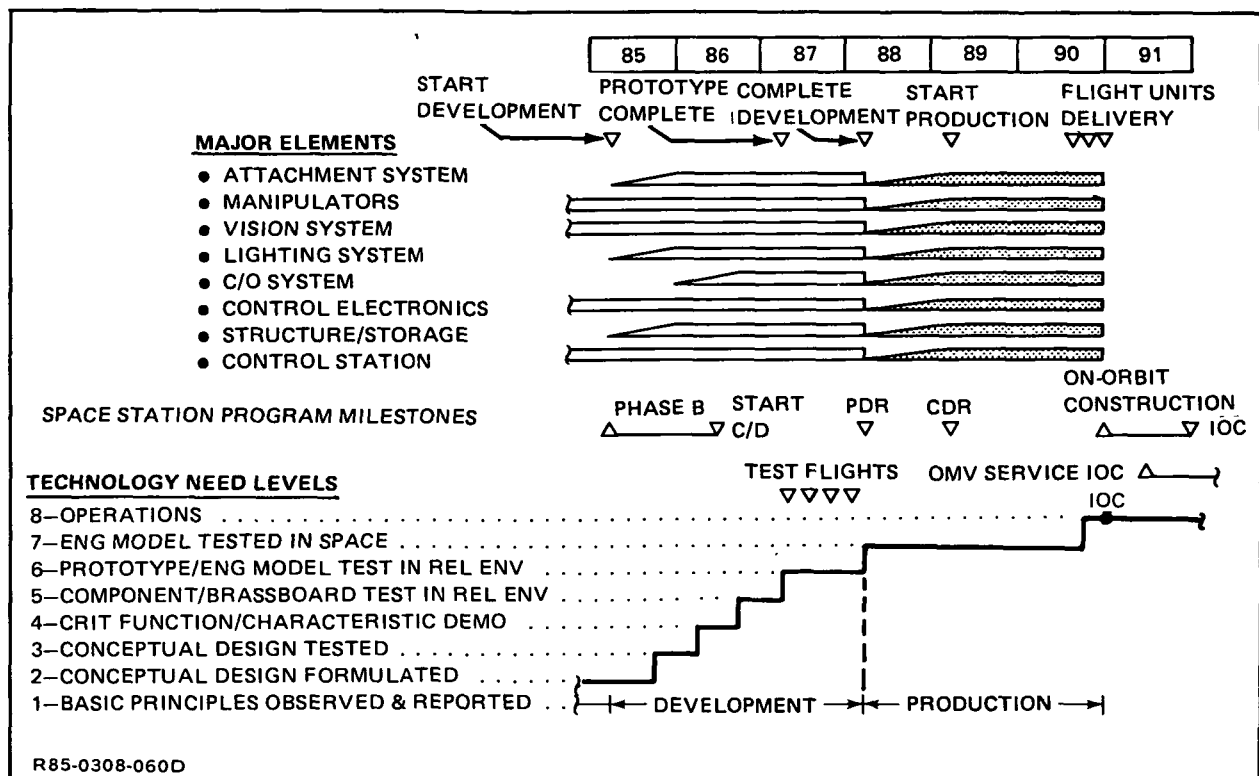


Fig. 5-25 Remote Work System Development

under development as shown. A three year flight development program leads to proof-of-concept test flights to support the space station Preliminary Design Review (PDR). Full production approval could be made by space station Configuration Design Review (CDR). This schedule is the basis for the program cost estimates presented below.

5.8.3 Flight Test Concepts

The variety of subsystems and components needed as a technology base for the development of space-based remote servicing capability requires extensive testing and simulation. Flight tests and demonstrations of component and system performance are considered a necessary step in this development process.

The need for such flight demonstrations and tests can be combined with the concept of a Telepresence Work Station (TWS) to use the Space Transportation System as a flight test bed. The TWS is based on the *open cherrypicker* concept which involves an astronaut carried on the end of the Shuttle's Remote Manipulator System (RMS). The TWS concept (Fig. 5-26) involves manipulators, TV cameras, etc. carried by the RMS in place of the astronaut. Control of the system is provided by

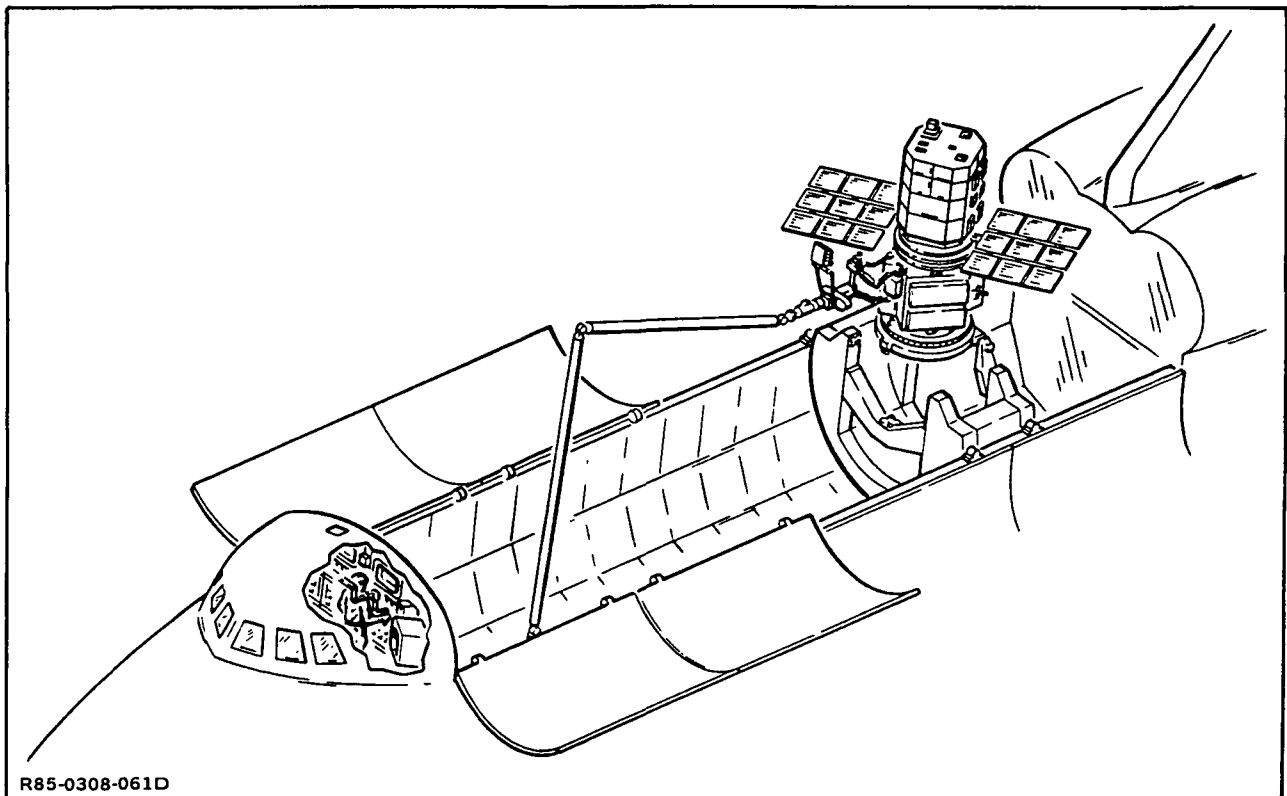


Fig. 5-26 Flight Demonstration Concept

an astronaut inside the Shuttle cabin to perform useful servicing operations. By configuring the TWS to accommodate different manipulators end effectors, sensors and control/communication links, a flight test bed results which provides a means of testing technology in the actual space environment. Such a concept is illustrated in Fig. 5-27.

5.8.4 Program Cost Estimates

Development and production costs for the remote work system were derived on the basis of system parameters including size, design factors, functional characteristics, and the program schedule presented earlier. The Parametric Review of Information for Costing and Evaluation (PRICE) model was used for all hardware components and PRICE-S was used to estimate the cost of software. The overall program consists of one prototype and three production flight units. Control station costs were not included.

The resulting cost estimates are presented in Fig. 5-28 which shows total cost as the sum of engineering and manufacturing costs for the development and production phases. The robotic system cost is almost 25% higher than the teleoperator

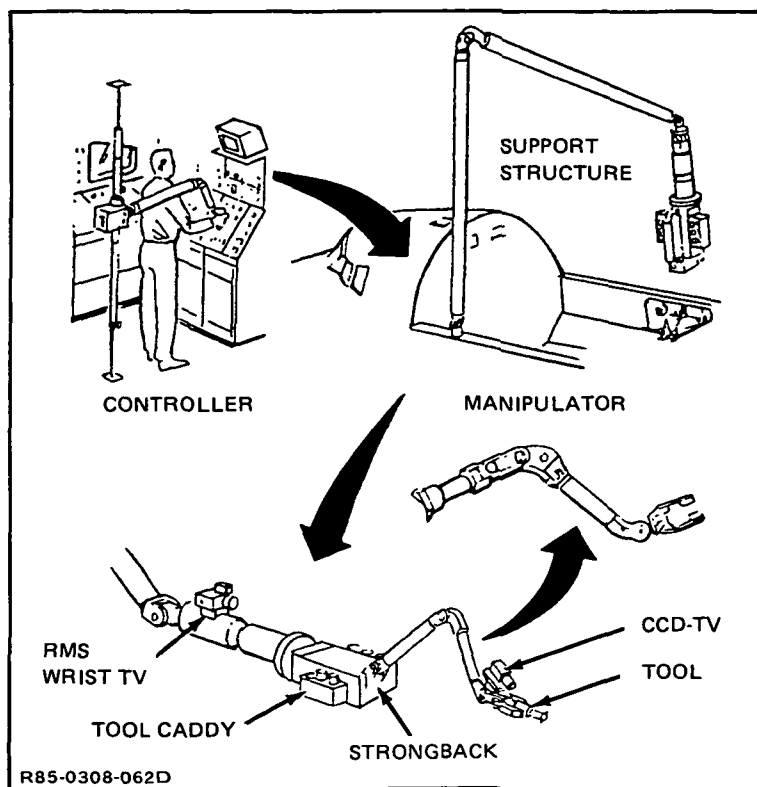


Fig. 5-27 Flight Test Bed Concept

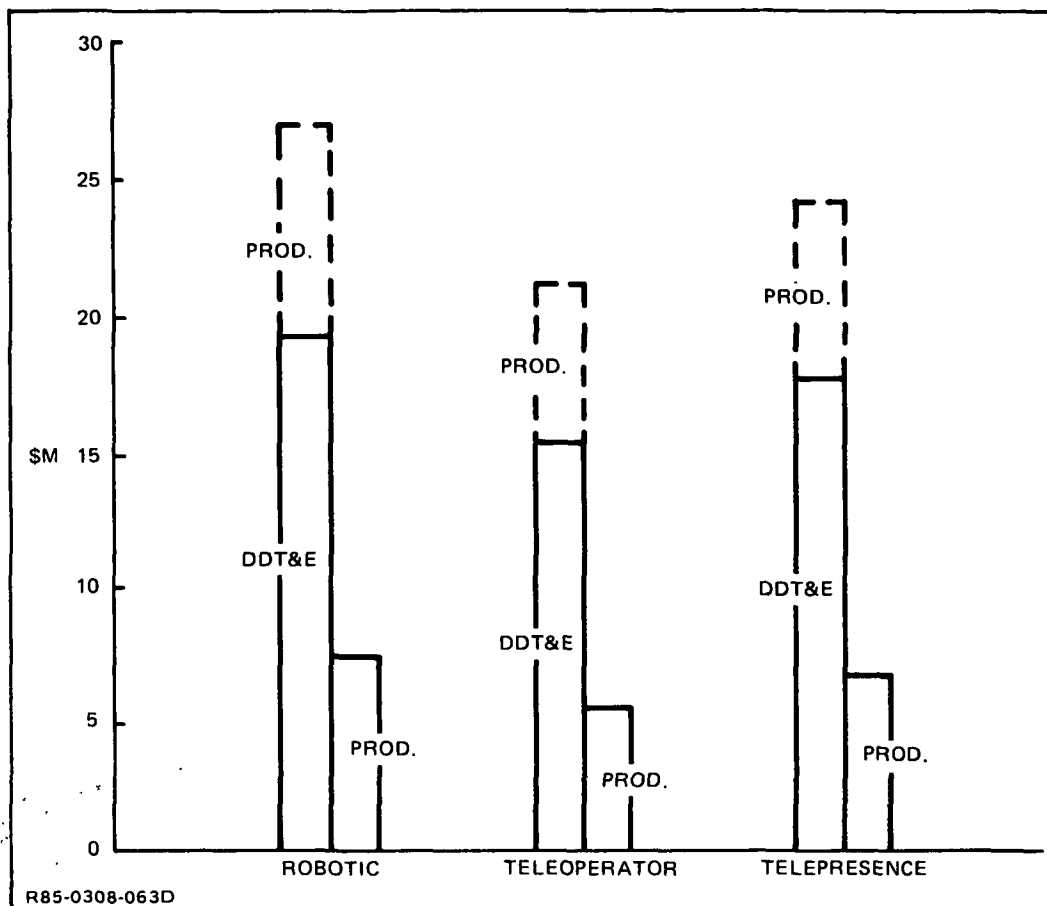


Fig. 5-28 Remote Work Systems — Relative Costs

approach, with the telepresence system in between. Development costs dominate the total costs in all cases.

The subsystem cost components are compared in Fig. 5-29 which shows that electronics contribute more than half of the total costs in all cases. The higher robotic system cost is primarily due to the more complex electronics at the remote site required for autonomous sensing and control. The telepresence system cost is high because it includes some of these features and because it has two, more-complex manipulators.

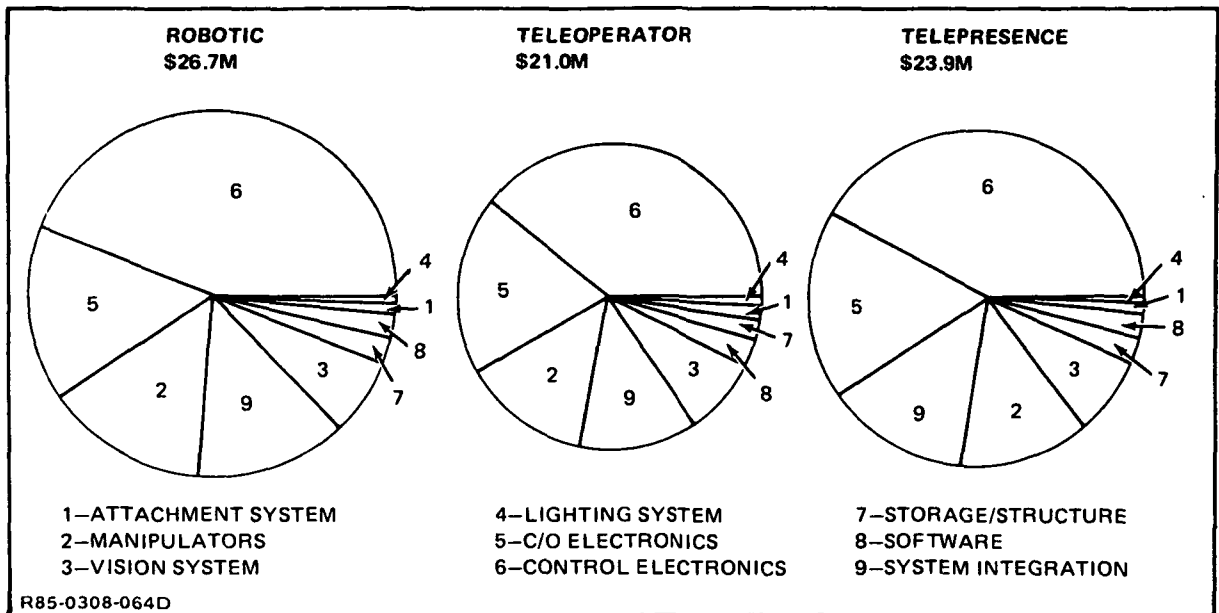


Fig. 5-29 Remote Work Systems/Elements Comparative Cost

6 - REFERENCES

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